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THESIS

IMPROVING THE RESILIENCY OF THE NATURAL GAS SUPPLY AND DISTRIBUTION NETWORK

by

John Nadeau

March 2007

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13. ABSTRACT (maximum 200 words)

To accommodate the nation's escalating demand for natural gas, which is expected to increase 700% by 2030, the natural gas industry will likely build several new liquefied natural gas (LNG) import terminals. The location of these new terminals is an important strategic decision that significantly impacts the resiliency of the nation's natural gas supply and distribution network. Due to public opposition in many communities and shortcomings in the current licensing process, any additional LNG import terminals are apt to be concentrated along the Gulf Coast. Unfortunately, this impending concentration will increase the vulnerability and diminish the resiliency of this critical infrastructure.

This thesis uses network theory to forecast how the location of new terminals will impact the risk, vulnerability, and resiliency of the natural gas supply and distribution network. To enhance the resiliency and reduce the vulnerability of this critical infrastructure, we argue network analysis methodology should be applied during the terminal siting process. The Federal government must act quickly to facilitate siting of terminals in locations that reduce the vulnerability and improve the resiliency of the natural gas network. Failure to act will squander an unprecedented opportunity to shape and intelligently design this portion of the nation's critical infrastructure.

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IMPROVING THE RESILIENCY OF THE NATURAL GAS SUPPLY AND DISTRIBUTION NETWORK

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To accommodate the nation's escalating demand for natural gas, which is expected to increase 700% by 2030, the natural gas industry will likely build several new liquefied natural gas (LNG) import terminals. The location of these new terminals is an important strategic decision that significantly impacts the resiliency of the nation's natural gas supply and distribution network. Due to public opposition in many communities and shortcomings in the current licensing process, any additional LNG import terminals are apt to be concentrated along the Gulf Coast. Unfortunately, this impending concentration will increase the vulnerability and diminish the resiliency of this critical infrastructure.

This thesis uses network theory to forecast how the location of new terminals will impact the risk, vulnerability, and resiliency of the natural gas supply and distribution network. To enhance the resiliency and reduce the vulnerability of this critical infrastructure, we argue network analysis methodology should be applied during the terminal siting process. The Federal government must act quickly to facilitate siting of terminals in locations that reduce the vulnerability and improve the resiliency of the natural gas network. Failure to act will squander an unprecedented opportunity to shape and intelligently design this portion of the nation's critical infrastructure.

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I. INTRODUCTION

"*As Hurricane Katrina demonstrated, infrastructure failure, regardless of cause, can exponentially amplify otherwise difficult but manageable consequences.*"

- William Webster, Acting Chair, Homeland Security Advisory Council[1]

A. PROBLEM

To meet the nation's demand for natural gas, imports of liquefied natural gas (LNG) are expected to increase more than 700% by 2030.[2] In response to this remarkable increase in demand, the natural gas industry will build several new import terminals to significantly expand the nation's LNG import capacity. For sound economic reasons, the natural gas industry is eager to construct new LNG import terminals in regions with the greatest demand, such as California and New England. However, much of the public perceives these terminals and the ships that service them as precariously vulnerable to terrorist attacks and an unacceptable hazard to the surrounding community. Because stiff local opposition can successfully derail efforts to site a facility, additional import terminals are apt to be concentrated along the relatively "LNG-friendly" Gulf Coast.

The natural gas supply and distribution network is comprised of the LNG import terminals, storage facilities, and interstate pipelines that connect them and deliver the natural gas to markets. This network is critical infrastructure in the energy sector. Though the siting of new LNG import terminals critically impacts the risk, vulnerability, and resiliency of the country's natural gas supply and distribution network, their affect on the network is not evaluated by the Federal government during the siting review and licensing process.

[1] Letter to Michael Chertoff, Secretary of Department of Homeland Security, dated February 14, 2006.

[2] Energy Information Administration, "Annual Energy Outlook 2006," February 2006, <http://www.eia.doe.gov/oiaf/archive/aeo06/index.html> (Accessed 23 September 2006).

As demonstrated by the devastating hurricanes that struck the Gulf Coast in 2005, the entire country assumes great liability if the oil and gas infrastructure continues to be concentrated in any one geographic area of the country. In addition to the vulnerabilities generated by this practice, the additional costs necessary to transport the natural gas from the Gulf to markets in the Northeast and West could cost billions of extra dollars.[3]

The impending expansion and alteration of the natural gas infrastructure provide an unprecedented opportunity to diversify the nation's energy supply and improve the resiliency of this important network. The siting decisions made today will significantly impact U.S. national security interests and economic stability for decades to come.

B. RESEARCH QUESTIONS

The primary questions investigated by this research are:

(1) Can network theory be used to predict what impact any given proposed LNG import terminal will have on the risk, vulnerability, and resiliency of the nation's natural gas supply and distribution network?

(2) Is it possible to predict how geographic concentration of new LNG import terminals will affect the network's risk, vulnerability, and resiliency?

(3) If network theory is capable of forecasting how proposed LNG import terminals will affect the future health of the natural gas supply and distribution network, how should these predictions be applied during the siting process?

C. METHODOLOGY

The existing natural gas supply and distribution system that services the Eastern half of the U.S. will be modeled using readily available data from the Energy Information Administration (EIA), U.S. Maritime Administration (MARAD), and Federal Energy Regulatory Commission (FERC).

[3] Paul Parfomak, *Liquefied Natural Gas (LNG) in U.S. Energy Policy: Infrastructure and Market Issues*, CRS Report for Congress (Washington, D.C.: GPO, 2005), 1.

Given all of the newly proposed and approved LNG import terminals, three possible growth scenarios are considered and, in each case, the resulting network is evaluated. One variation of the network includes all thirty nine of the approved or proposed LNG import terminals. Since experts doubt all of the approved or proposed terminals will be built, the other two variations include only eight of the approved or proposed LNG import terminals. One of the variations disperses the facilities throughout the network and the other configuration concentrates them along the Gulf coast.

Software developed by Lewis[4] is used to analyze each of the three network variations. These network analyses identify the critical components and determine the relative cost necessary to reduce vulnerability and risk and guarantee a certain quantity of natural gas flow. The resiliency of the dispersed and concentrated networks is assessed by evaluating how each network performs when individual network components are damaged. Analyses of the concentrated and dispersed networks are compared to illustrate the impact of geographically concentrating network components.

Lastly, the role and responsibility of the primary federal agencies involved in LNG import terminal siting and licensing are evaluated to identify methods to incorporate network assessment methodology into the siting evaluation process.

[4] Ted Lewis, *Critical Infrastructure Protection in Homeland Security: Defending a Networked Nation* (Indianapolis: Wiley, 2006).

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II. LNG IN THE U.S.

"...without more infrastructure, gas may face the kind of glut plaguing the electric utility industry, with too much generating capacity and too few connections."

– anonymous quote from member of natural gas industry[5]

A. LNG FUNDAMENTALS

Natural gas is an odorless, colorless, and non-toxic gas at ambient temperature. It is predominantly composed of methane (CH_4), but it includes varying amounts of other hydrocarbon gases, including ethane, propane, butane, and pentane. In addition, it will also contain various amounts of water, carbon dioxide, hydrogen sulfide, nitrogen, and other contaminants.

If cooled to - 260°F, natural gas condenses into a liquid and becomes liquefied natural gas, or as it is more commonly known, "LNG." It is a clear liquid that is less dense than water. Though the extremely cold temperature of the liquid requires special materials and procedures for storing and handling, the volume occupied by the natural gas is reduced 600 times when it is condensed into LNG. Consequently, the space needed to store LNG is only 1/600th the volume required to store the "equivalent" amount of natural gas. In the event of a leak, LNG quickly vaporizes into a gas, rises into the air, and forms a cloud.[6]

Though it is too costly to ship in the gas phase, transport of LNG in specially designed vessels can be economical, despite the significant investment in infrastructure that is necessary in order to properly handle and store the cargo. Historically, ships have been chartered and operated on a regular schedule between a specific gas field and an associated LNG terminal for as long as twenty five years. The marine terminal exporting the gas has a liquefaction plant that condenses the natural gas into LNG and loads it aboard the ship, which then transports it to a terminal in the U.S. where it is offloaded

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[5] Parformak, *Liquefied Natural Gas*, 13.

[6] Alain Vaudolon, *Liquefied Gases Marine Transportation and Storage* (London: Witherby & Company Limited, 2000), 7.

and stored in tanks. In response to demand, the LNG is regasified and delivered into the pipeline network.

In 1959, the METHANE PIONEER, a converted WWII dry cargo vessel, became the first ship in the world to transport LNG. The vessel successfully carried 5,000 m^3 of LNG from Lake Charles, Louisiana to the United Kingdom. In 1964, the first vessels purposely built to carry LNG were delivered. Each had a capacity of 27,400 m^3 and operated safely for many years. Similarly, the 25,550 m^3 JULES VERNE was built in 1965 and, in 2000, was reportedly still carrying LNG from Algeria to Spain, representing thirty four years of service and nearly 1,200 voyages.[7]

Figure 1. Typical LNG Tank Ship (From FERC <http://www.ferc.gov/press-room/photo-gallery/photo-gallery-lng.asp>)

The size of LNG ships increased quickly, growing to 125,000 m^3 by the middle of the 1970s. The average LNG ship in service today can carry approximately 138,000 m^3 of cargo. Surprisingly, the LNG is not refrigerated or stored under pressure while aboard the ship. The tanks have maximum operating pressure of only approximately one or two psia and insulate the LNG from the warmer ambient temperature surrounding the tank.

In 2000, there were only 117 LNG ships trading around the world. By January of 2007, there were an additional 134 new LNG tank ships either under construction or on order.[8]

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[7] Vaudolon, *Liquefied Gases*, 22.

[8] Maritime Business Strategies, *The Orderbook of LNG Carriers (as of January 1, 2007)*, <http://www.coltoncompany.com/shipbldg/worldsbldg/gas/lngorderbook.htm> (Accessed 8 January 2007).

Figure 2. Cargo Tanks Installed in New LNG Tank Ship (From Sandia National Laboratories, *Guidance on Risk Analysis and Safety Implications of a Large LNG Spill Over Water*).

B. INCREASING DEMAND

As shown in Figure 3, imports of LNG into the United States have grown dramatically over the past ten years.[9] In 2004, a record-high 650 billion cubic feet (Bcf) of LNG was imported from seven different countries, amounting to a 30% increase from 2003. In 2005, the EIA estimated the annual U.S. LNG demand would grow to 6,400 Bcf cubic feet by 2025.[10] Though current predictions for the LNG demand have fallen from previous estimates, the most recent predictions still estimate annual LNG imports to increase 733% to 4,400 Bcf by 2030.[11]

[9] Energy Information Administration, *Natural Gas Navigator*, <http://tonto.eia.doe.gov/dnav/ng/hist/n9103us2A.htm> (Accessed 22 April 2006).

[10] Energy Information Administration, "Annual Energy Outlook 2005," February 2005, <http://www.eia.doe.gov/oiaf/archive/aeo05/index.html> (Accessed 8 January 2007).

[11] Energy Information Administration, "Annual Energy Outlook 2006," February 2006, <http://www.eia.doe.gov/oiaf/archive/aeo06/index.html> (Accessed 23 September 2006).

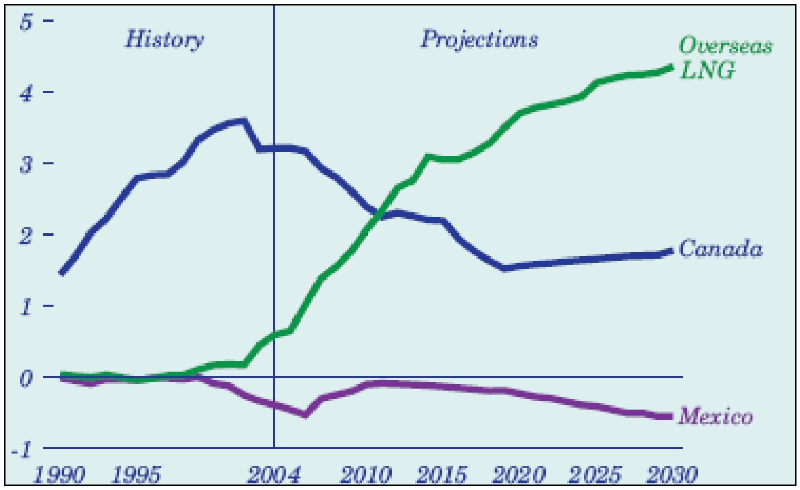

Figure 3. Predicted Annual LNG Imports in Trillions of Cubic Feet (From the Energy Information Administration, "Annual Energy Outlook 2006").

The projected growth in U.S. demand is due, in part, to the decrease in natural gas shipments via pipeline from Canada.[12] While Canada's supply continues to diminish, natural gas demand in the U.S. continues to increase. The rising demand will be met by increasing LNG imports, which will require a significant increase in the number of LNG import terminals.

C. GROWING INFRASTRUCTURE

As shown in Figure 4, there are presently six shore-side LNG terminals operating in the U.S. However, only four of them are capable of supplying natural gas to the 48 contiguous states. Ironically, the facility in Kenai, Alaska, which commenced operation in 1969, is used to export natural gas from Alaska to Japan because there are no LNG import terminals on the West coast.[13] A small LNG import terminal located approximately nine miles west of Ponce, Puerto Rico, provides gas to a power plant that supplies electricity to the island, but is also isolated from the continental U.S.

The other four shore-side LNG import terminals were built in the 1970's and the amount of LNG imported to the continental U.S. gradually increased until it peaked in

[12] Energy Information Administration, "U.S. Natural Gas Imports and Exports 2004," <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2005/ngimpexp/ngimpexp.pdf> (Accessed 21 April 2006), 3-4.

[13] Vaudolon, *Liquefied Gases*, 27.

1979. Although two of the terminals were closed in 1980, domestic demand slowly returned and all four terminals are now back in operation.

The Gulf Gateway Energy Bridge, an offshore LNG import terminal located approximately 116 miles off the coast of Louisiana in the Gulf of Mexico, commenced operation in 2005. This unique facility consists of only a specially designed buoy anchored to the seafloor. Specially designed LNG tank ships, which are equipped with extensive vaporization equipment that is normally located at shore-side LNG import terminals, mate to the buoy, regasify the LNG, and pump the natural gas into a submerged pipeline and directly to market.

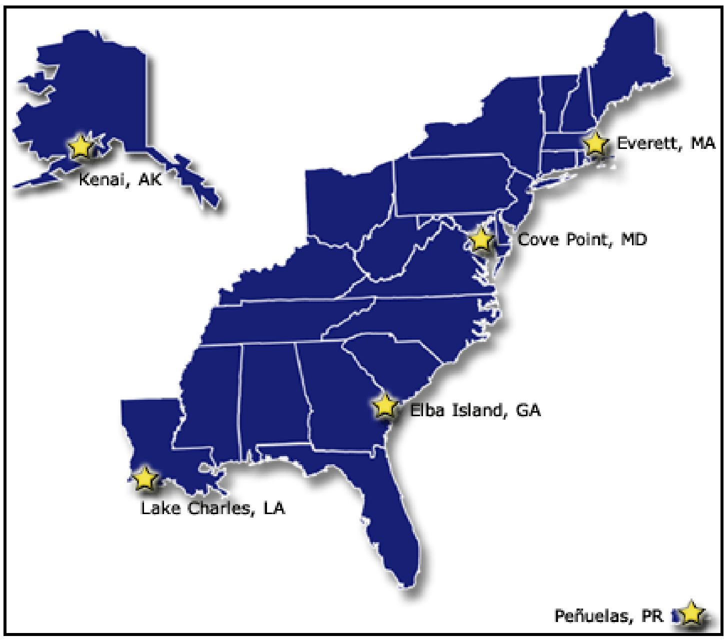

Figure 4. Existing Shore-side LNG Facilities (From Federal Energy Regulatory Commission, "Existing and Proposed LNG Terminals" <http://www.ferc.gov/industries/lng/indus-act/terminals/exist-prop-lng.pdf>).

Alan Greenspan, then Chairman of the Federal Reserve, in testimony before the House Committee on Energy and Commerce in 2003, noted that a "major expansion" of North American LNG terminal import capacity is needed for the U.S. natural gas market to function properly.[14] As shown in Figure 5, nineteen new import facilities have been approved and twenty more have been proposed for the U.S. However, since only six to

[14] House Committee on Energy and Commerce, *Natural Gas Supply and Demand Issues*, 108th Cong., 2nd sess., 2003.

twelve new facilities are necessary to properly meet the anticipated increase in demand, not all of these facilities are expected be built.[15, 16]

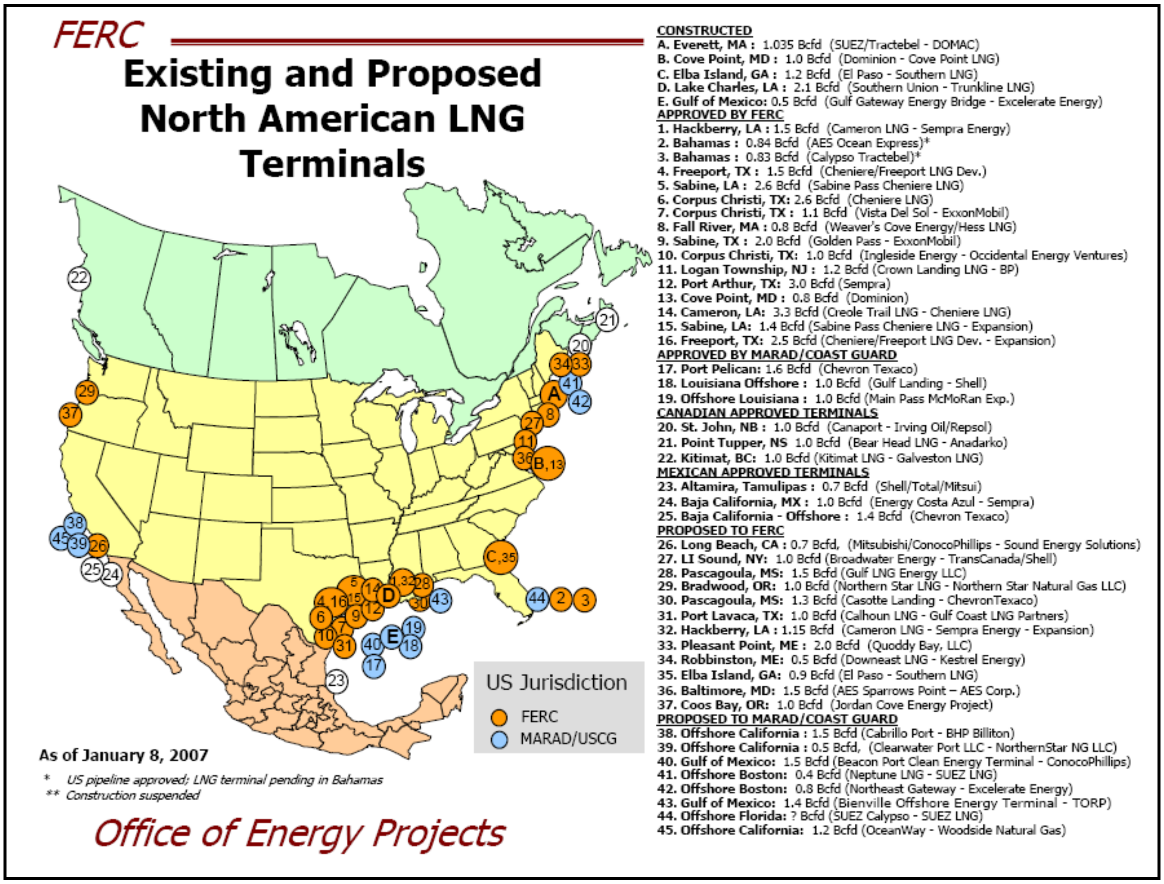

Figure 5. Proposed Shore-side LNG Facilities (From Federal Energy Regulatory Commission, "Existing and Proposed LNG Terminals," <http://ferc.gov/industries/lng/indus-act/terminals/exist-prop-lng.pdf >).

The location of three of the existing facilities and the majority of the proposed facilities along the Gulf coast are separated from the expanding markets in the Northeast and West by great distances. As shown in Figures 6 and 7, more than 213,000 miles of interstate pipelines transport natural gas from the Gulf Coast to markets across the U.S.[17]

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[15] Parfomak, *Liquefied Natural Gas*, 1.

[16] Federal Energy Regulatory Commission, "Industries: Liquefied Natural Gas," <http://www.ferc.gov/industries/lng.asp#howmany > (Accessed 28 October 2006).

[17] Energy Information Administration, "Additions to Capacity on the U.S. Natural Gas Pipeline Network: 2005," August 2006, <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngpipeline/ngpipeline.pdf> (Accessed 30 October 2006), 4.

In the past, LNG imports represented such a small share of the natural gas market that the location of import terminals had little influence on development of the pipeline network. Given the tremendous investment associated with the development of additional pipelines, new import terminals located in the Gulf are likely to rely on the existing pipeline infrastructure to move gas to markets.

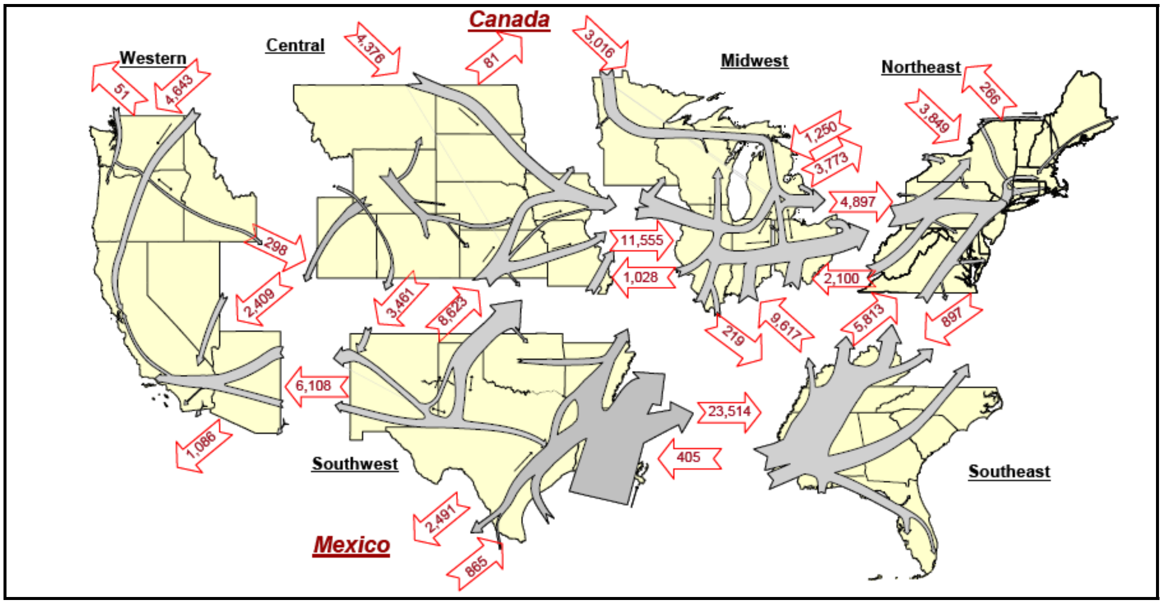

Figure 6. Natural Gas Pipeline Flow in Millions of Cubic Feet Per Day (MMcf/d)(From the Energy Information Administration, "Additions to Capacity on the U.S. Natural Gas Pipeline Network: 2005," <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngpipeline/ngpipeline.pdf>).

Natural gas is stored in underground facilities, such as salt domes and depleted natural gas or oil reservoirs. In addition to meeting demand during peak times, the stored gas is used to balance the pressure in pipelines and is important to the proper operation of the entire natural gas supply and distribution network.[18] As shown in Figure 7, there is no natural storage in New England or along the East coast and limited amounts in the West.

[18] Energy Information Administration, "U.S. Underground Natural Gas Storage Developments: 1998-2005," October 2006, <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2006/ngstorage/ngstorage.pdf > (Accessed 8 January 2006), 2.

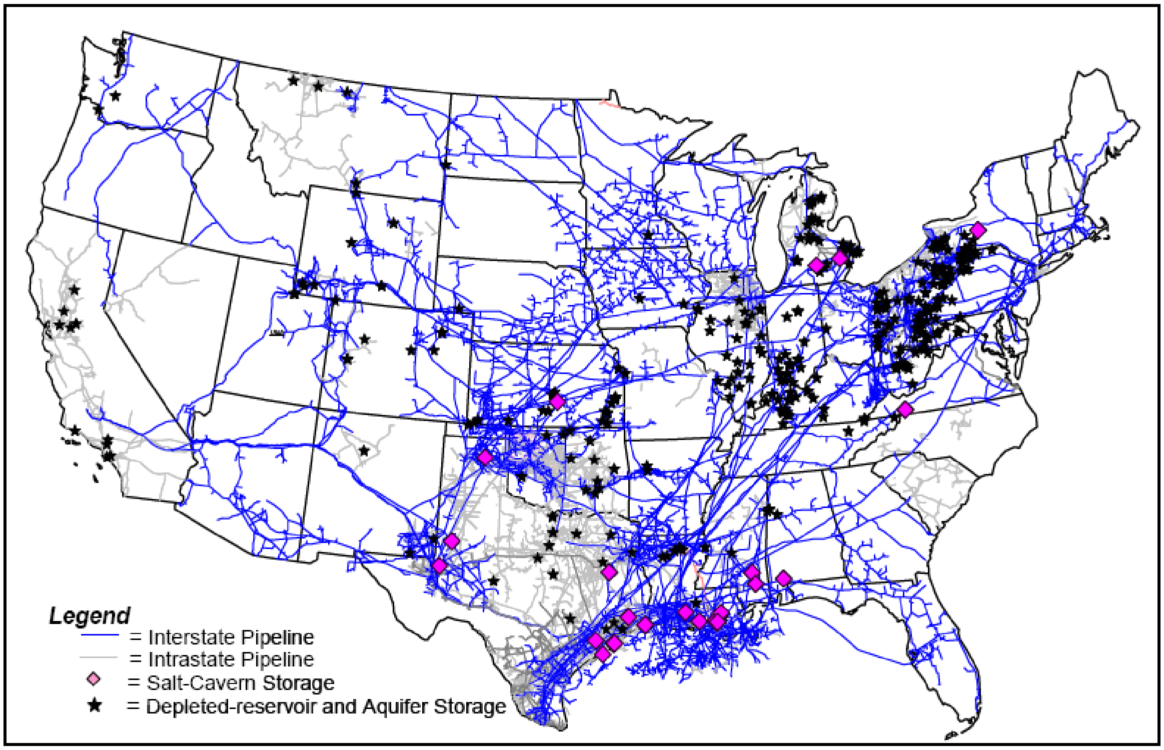

Figure 7. Location of Pipelines and Underground Natural Gas Storage Facilities (From the Energy Information Administration, "U.S. Underground Natural Gas Storage Developments 1998 – 2005").

In summary, natural gas production and infrastructure is largely concentrated along the Gulf coast. An extensive interstate pipeline system transports the natural gas to markets throughout the country. The natural gas industry is on the cusp of an unprecedented surge in investment and development of several new LNG import terminals, each of which will be subjected to the siting and licensing requirements established by the federal government.

D. SITING AUTHORITY AND REQUIREMENTS

"The goal of the FERC's LNG Program is to ensure that projects which are found to be in the public interest are constructed and operate in a safe and secure fashion."

- Mark Robinson, Director of Office of Energy Project, FERC[19]

Federal jurisdiction over LNG facilities is shared by the Federal Energy Regulatory Committee (FERC), Department of Transportation (DOT), and the U.S. Coast Guard (USCG).[20] The jurisdictions and responsibilities of these agencies are intertwined and confusing.

Under the Natural Gas Pipeline Safety Act of 1968 and subsequent legislation, DOT is responsible for establishing minimum safety standards for siting, design, construction and operation of LNG facilities. The Pipeline Safety Act of 1994, which recodified the Natural Gas Pipeline Safety Act of 1968, requires DOT to prescribe the minimum standards for deciding the location of a new LNG facility.[21] In doing so, DOT is to consider the local population and demographics, surrounding property, and the ability of local resources to cope with risk created by the facility. DOT also establishes minimum safety standards for the design, installation, construction, inspection and testing of LNG terminals.

The FERC has exclusive authority to grant federal approval for siting of all LNG terminals, except LNG deepwater ports. Proposed LNG facilities are evaluated by FERC to ensure they comply with the minimum standards established by DOT. The FERC's approval is always conditioned on the ability of the facility to satisfy other statutory requirements contained in the Clean Water Act, Coastal Zone Management Act, and

[19] Senate Committee on Energy and Natural Resources, Subcommittee on Energy, *The Future of Liquefied Natural Gas: Siting and Safety*, 109th Cong., 2nd sess., 2005.

[20] Federal Energy Regulatory Commission, "Interagency Agreement Among the FERC, USCG and RSPA for the Safety and Security Review of Waterfront Import/Export LNG Facilities," <http://www.ferc.gov/industries/lng/safety/reports/2004-interagency.asp> (Accessed 16 October 2006).

[21] Title 49 U.S. Code, sec. 60103, <http://frwebgate5.access.gpo.gov/cgi-bin/waisgate.cgi?WAISdocID=966974425309+0+0+0&WAISaction=retrieve> (Accessed 9 January 2007).

Clean Air Act.[22] Compliance with these requirements is determined by each individual state and construction can be blocked if the state determines the proposed LNG facility fails to meet one or more of these requirements and decides to withhold one or more of the necessary certificates or approvals.

The FERC's authority is derived from the Natural Gas Act of 1938, delegated from the Energy Secretary, and implemented in 18 C.F.R. Part 153.[23] Specifically, the FERC has the authority to approve the place of entry and exit, siting, construction, and operation of new LNG terminals. In accordance with the National Environmental Policy Act of 1969, FERC prepares an environmental impact statement for each proposed LNG terminal. Applicants are required to submit thirteen different Resource Reports that analyze various aspects of the proposed terminal. Resource Report 11, *Reliability and Safety*, addresses potential hazards to the public from failures caused by "accidents and natural catastrophes" and discusses "how these events would affect reliability [of natural gas supply]."[24] This report must discuss measures to protect the public from failure of the proposed facility, efforts to reduce risk, and contingency plans.

LNG terminals floating or attached to the seabed beyond state waters are, by definition, LNG deepwater ports and are not authorized by FERC. Under the Maritime Transportation Security Act of 2002, DOT is responsible for approving LNG deepwater ports; however, DOT delegated this authority to the Maritime Administration (MARAD) in June of 2003. Although MARAD grants the approval, the USCG conducts the engineering, operations, safety, and environmental review of LNG deepwater ports, which are often referred to as "offshore" LNG terminals. Though they must also comply with the National Environmental Policy Act, offshore LNG terminals are subject to different requirements than onshore terminals and must satisfy the standards in 33 C.F.R. Parts 148 through 150. Since the governor of each adjacent coastal state has to grant

[22] Federal Energy Regulatory Commission, "LNG – Laws and Regulations," <http://www.ferc.gov/industries/lng/gen-info/laws-regs/state-rights.asp> (Accessed 9 January 2007).

[23] Federal Energy Regulatory Commission, "Testimony of Pat Wood III, Chairman, Federal Energy Regulatory Commission before Subcommittee on Energy Policy, Natural Resources, and Regulatory Affairs, Committee on Government Reform, US House of Representatives, June 22, 2004," <http://ferc.gov/congress/cong-test/2004/06-22-04-wood.pdf> (Accessed 10 December 2006).

[24] Title 18 U.S. Code of Federal Regulations, sec 380.12(m), <http://a257.g.akamaitech.net/7/257/2422/10apr20061500/edocket.access.gpo.gov/cfr_2006/aprqtr/18cfr380.12.htm> (Accessed 12 January 2007).

approval before MARAD can authorize and license a new offshore LNG terminal, they have the authority to veto any proposal and are capable of blocking development of any LNG deepwater port.[25]

E. SECURITY REQUIREMENTS

The security requirements applicable to LNG terminals are contained in several different regulations. Although these requirements may address the security of each individual facility, none of them consider the entire LNG supply and distribution network. The vulnerability and impact of the proposed facilities on the critical infrastructure of the energy sector is not considered as part of the current siting review process.

The DOT's security regulations for onshore LNG terminals simply require posting of "No Trespassing" signs and only address site specific issues such as lighting, access control, monitoring, and communications.[26] Similarly, security requirements enforced by the USCG as part of the of the Ports and Waterways Safety Act (PWSA) of 1972 only discuss limiting access to the LNG transfer area, security patrols, protective enclosures for transfer control stations, and communications between facility personnel.[27]

The PWSA requires the USCG to evaluate waterways impacted by new LNG terminals and determine their suitability for LNG marine traffic. This assessment must consider the density and character of vessel traffic, natural and man-made obstructions and hazards, and the mooring arrangements of the LNG tank ships.[28]

Although the PWSA does not explicitly specify security standards, the USCG modified its procedures in 2005 to include some security considerations in its review and

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[25] Energy Information Administration, "2002 Amendments to the Deepwater Port Act of 1974," http://www.eia.doe.gov/oil_gas/natural_gas/analysis_publications/ngmajorleg/amendments.html > (Accessed 11 January 2007).

[26] Title 49 U.S. Code of Federal Regulations, sec. 193.2901 – 2917.

[27] Title 33 U.S. Code of Federal Regulations, sec. 127.701 – 711.

[28] Title 33 U.S. Code of Federal Regulations, sec. 127.209.

assessment of the waterway.[29] With the unique aspects of the waterway in mind, a risk analysis is conducted to address the safety and security of LNG tank ships, public health and safety, protection of other critical infrastructure and key assets in the area, and consequence management. Findings and recommendations regarding the suitability of the waterway are provided to the FERC for consideration as part of the environmental impact statement and used to develop a formal recommendation for those state and local agencies that have jurisdiction. In accordance with the Maritime Transportation Security Act of 2002, all LNG terminals must undergo security assessments, develop security plans, and undergo examinations to verify compliance.[30]

Despite efforts to improve the security of U.S. ports, the country remains vulnerable to terrorist attacks in its ports and waterways.[31] Terrorists have clearly demonstrated the ease and effectiveness of suicide attacks using vessel-borne improvised explosive devices (VBIEDs). The National Strategy for Maritime Security concedes this mode of attack "has been established, tested, and repeated."[32] Prevention of suicide attacks is particularly difficult in ports and harbors, where ships are restricted from movement and are regularly in close proximity to many other vessels, including commercial fishing vessels, recreation boats, tug boats, and line handlers.

To help address these risks, LNG tank ships are typically escorted to the LNG terminal by the USCG. A Security Zone is established around the vessel to restrict other ships from approaching it. For instance, each time a tank ship enters Boston harbor to deliver LNG at the import in Everett, Massachusetts, a team from the local USCG office boards the vessel, airplane traffic in and out of Logan Airport and vehicle traffic over the Tobin bridge are suspended, and six tug vessels, two of which have advanced fire

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[29] U.S. Coast Guard, "Navigation and Vessel Inspection Circular 05-05, Guidance on Assessing the Suitability of a Waterway for Liquefied Natural Gas (LNG) Marine Traffic," June 14, 2005, <http://www.uscg.mil/hq/g-m/nvic/NVIC%2005-05.doc.pdf> (Accessed 15 November 2006), 4.

[30] Title 33 U.S. Code of Federal Regulations, sec. 105.

[31] House Committee on Transportation and Infrastructure, Subcommittee on Coast Guard and Maritime Transportation, *Port Security Oversight*, Testimony by RADM Craig E. Bone, 109th Cong., 1st sess., 29 June 2005.

[32] United States White House, *The National Strategy for Maritime Security* (Washington, D.C.: White House, 2005), 4.

fighting capabilities, accompany the vessel.[33] Though not identical, specific procedures are adopted in other ports to address the risk presented by LNG vessels.

As the number of facilities and frequency of tanker shipments increases, the costs necessary to provide these security measures and mitigate the risks also grow. In addition, they increase the burden on the USCG, local law enforcement and other emergency response agencies. Some people have suggested it may become necessary for the LNG industry to help fund the security or provide a mechanism for government to recoup costs.[34]

In summary, the safety and security requirements address the individual LNG terminal under consideration and its potential impact on the local community. However, although it could affect an entire region of the country, the review process does not consider how damage or loss of a proposed LNG import terminal affects the nation's natural gas supply and distribution.

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[33] Alan M. Herbst, "LNG Threat to Public Safety Probably Small, but Security Essential," *Natural Gas & Electricity* (September 2004): 13.

[34] Parfomak, *Liquefied Natural Gas*, 20.

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III. FEAR OF LNG

"LNG has polarized the entire community."

- Director of community development organization in Harpswell, Maine[35]

A. INCIDENT HISTORY

LNG tank ships have made more than 33,000 safe transits since they began carrying LNG in 1959. However, there have been only thirteen serious incidents at LNG terminals around the world.

The first accident at a U.S. LNG facility occurred in 1944 at a "peak shaving" facility, which stores LNG for use during periods of peak demand. Due to shortages in stainless steel alloys, less suitable materials were used to construct a storage tank in Cleveland, OH. Consequently, the tank failed almost immediately after it was placed in service. The LNG vaporized and formed a cloud of natural gas that drifted into a residential area before igniting and causing 128 deaths.[36]

In 1977, an accident at a terminal in Algeria killed one person. Two years later, a leak at the LNG import terminal in Cove Point, Maryland, resulted in the death of one individual. A faulty pump seal permitted LNG to escape, vaporize, and spread through underground electrical conduit to a substation, where the gas ignited and caused an explosion. More recently, a boiler explosion killed twenty seven workers at a large LNG facility in Algeria.[37]

B. "EXPERT" PREDICTIONS

Since the attacks on September 11, 2001, studies have been conducted to assess the safety hazards created by LNG terminals and tank ships. Because large scale testing

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[35] Anne Ravana, "Fisherman Split over LNG Terminal Proposals," *Bangor Daily News,* 7 September 2006, <http://bangordailynews.com/news/t/statewide.aspx?articleid=142764&zoneid=500> (Accessed 7 September 2006).

[36] Herbst, *LNG Threat to Public Safety*, 10.

[37] Paul Parformak and Aaron Flynn, *Liquefied Natural Gas (LNG) Import Terminals: Siting, Safety & Regulation*, CRS Report for Congress (Washington, D.C.: GPO, 2004), 7.

has not been conducted, there are significant differences in the modeling, assumptions, and resulting conclusions. The disagreement and inconsistency between the experts has produced controversy and confusion. In an attempt to resolve the professional conflict, Sandia National Laboratories reviewed and compared the different studies. However, the comprehensive report concluded that the "risks from accidental spills… are small and manageable…" but the "consequences from an intentional breach [of a cargo tank on an LNG tank ship] can be more severe than those from accidental breaches."[38] Similarly, a study released by the FERC stated it was only possible to provide "rough estimates" of the effects of large LNG releases on water because of the uncertainty inherent in the analysis methods.[39]

As a result, both proponents and opponents believe the report supports their position and the ensuing controversy has yet to be resolved.[40] The failure of experts to reach a consensus is fueling fears, leaving many community members to question the ability of government agencies to accurately assess the hazards.

C. TENSION IN THE COMMUNITY

"*They [LNG industry representatives] don't really come out and answer questions…. They beat around the bush.*"

- Chairman of local fisherman's association in Harpswell, Maine[41]

The public's anxiety and fear has led to the emergence of the NIMBY ("Not in My Backyard") phenomenon, whereby people are passionately opposed to the introduction of LNG terminals into their neighborhoods and communities.[42] Sufficient

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38 Mike Hightower et al., *Guidance on Risk Analysis and Safety Implications of a Large Liquefied Natural Gas (LNG) Spill Over Water,* Sandia National Laboratories, December 2004, <http://www.fossil.energy.gov/programs/oilgas/storage/lng/sandia_lng_1204.pdf> (Accessed 12 September 2006), 14.

39 ABS Consulting, *Consequence Assessment Methods for Incidents Involving Releases from Liquefied Natural Gas Carriers*, 13 May 2004 <http://ferc.gov/industries/lng/safety/reports/cons-model.pdf> (Accessed 12 September 2006), iii.

40 Parfomak, *Liquefied Natural Gas*, 7.

41 Ravana, "Maine Fisherman Split Over LNG Terminal Proposals."

42 Frank Fischer, *Citizens, Experts, and the Environment: The Politics of Local Knowledge* (London: Duke University Press, 2000), 122.

local opposition can defeat any proposed project, regardless of its importance to the region or country.[43] Consider New England, where the limited availability of natural gas during peak demands in the winter of 2004 forced operators to limit distribution and shut down more than half of the gas-fired generators in New England.[44] Despite these shortages, proposals to bring LNG into the Northeast are being met with stiff opposition.

In addition to concerns regarding accidental failures, people who will live and work near the terminals fear well-planned deliberate attacks by terrorists who openly admit to targeting the energy sector's critical infrastructure. The inability of experts to reach a consensus on the vulnerabilities and consequences of an incident involving a ship loaded with LNG is creating additional confusion and concern.

Fear and security concerns related to LNG became immediately apparent in the aftermath of 9/11 when officials in Boston, Massachusetts refused to let the LNG tank ship MATTHEW enter port to discharge its cargo. Though it had been carrying LNG on a regularly scheduled route and transiting under the Tobin Bridge and past Logan Airport to the Distrigas Terminal every week for years, officials now feared that the ship may be attacked by terrorists and refused to let it enter port.[45]

This type of fear and opposition is not limited to communities in the Northeast. More than 1,000 people, including many Hollywood celebrities, attended an event in Malibu, California to protest siting of the first import terminal on the West coast. Actor Pierce Brosnan stated construction of the terminal would have "disastrous consequences" and Ted Danson argued that the community was selected for the terminal because industry viewed it as weak and unable to fight.[46]

The public's fears and suspicions are reflected in the actions of elected officials. After a LNG import terminal proposed for Fall River, Massachusetts was approved by FERC, the Rhode Island House of Representatives unanimously passed legislation to

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43 Paul Hibbard, *Demand, Supply and Facility Siting, Report to the National Commission on Energy Policy* (Boston: Analysis Group, Inc., 2004), 19.

44 Hibbard, *U.S. Energy Infrastructure*, 11.

45 Marine Log, "LNG Matthew Banned from Boston," *Marine Log* (27 September 2001), <http://www.marinelog.com/DOCS/NEWSMMI/MMISep27.html > (Accessed 10 January 2007).

46 Kriss Perras Running Waters, "Pierce Brosnan Brings out Malibu's Hollywood Power to Oppose LNG," *PCH Press*, 22 October 2006. <http://www.pchpress.com/> (Accessed 25 October 2006).

block LNG tank ships from transiting Narragansett Bay, which is the only way for them to get to the terminal.[47] This was after representatives from Massachusetts managed to insert language into a transportation bill to prevent demolition of a draw bridge that restricts the width of ships which may pass, essentially making it impossible for existing LNG tank ships to reach the proposed terminal. Though the bridge is being replaced, the legislation provided $500,000 to modify the obsolete bridge and use it for bicycle and pedestrian traffic.[48] The company seeking to build the terminal indicated they would overcome this obstacle by making more frequent trips with "skinnier" LNG tank ships especially designed for this transit. FERC considered the increased traffic caused by using smaller ships and reaffirmed its previous approval, but elected officials from Massachusetts stated the project should not be permitted to go forward due to the excessive risk to the community.[49]

Figure 8. LNG Tank ship transiting beneath the Tobin Bridge in Boston (From <http://www.seafarersfriend.org/where/index.html>).

[47] Joe Baker, "House Bill Would Block LNG Tankers from R.I. Waters" *Newport Daily News*, 11 May 2006, <http://www.newportdailynews.com/articles/2006/05/11/news/news6.txt> (Accessed 11 May 2006).

[48] Jim Snyder, "Fight Over Gas Terminal May Go A Bridge Too Far" *Hill*, 2 May 2006, <http://www.hillnews.com/ > (Accessed 2 May 2006).

[49] Brian Boyd, "Coast Guard Opposition Sought in LNG Battle" *New Bedford Standard-Times*, 20 April 2006, < http://www.southcoasttoday.com/ > (Accessed 20 April 2006).

Frustrated experts and industry leaders often claim the public is irrational, ignorant, and incapable of understanding the technical information they believe demonstrates the risk is low.[50] Some senior representatives in federal agencies responsible for approving new terminals and pipelines have similar opinions.[51] Mark Robinson, the Director of the Office of Energy Projects at FERC, has suggested the communities opposed to the introduction of LNG import terminals are naïve and susceptible to misinformation:

> When we [FERC] go into areas of the country that have a history of dealing with the petrochemical industry, they're still very willing to listen to the facts and incorporate their concerns and comments and deal with it from there. In other areas of the country, where they're not quite as used to dealing with the petrochemical industry, it takes only one or more nonfactual statements to get out to folks and put them in a mode where they believe things about LNG that just flatly aren't true.[52]

Is the public behaving selfishly? Not likely. Of course, all persons on different sides of any issue have their own interests in mind. With the siting of a LNG import terminal, opponents are concerned with property values, pollution, and impacts on their personal security and health. Though they may wish people to believe they are only trying to increase supply or improve the energy reliability for the nation, the company seeking to build the terminal is interested in making a profit. Other proponents for the terminal are just as likely to be persuaded by the personal economic benefits they may receive.

Is the public ignorant or irrational? The issue is not simply a matter of ignorance or rationality. The citizens in the community view risk differently than the experts and scientists.[53] The experts apply science in an objective manner based on clearly defined principles and norms. However, lay people in the community also consider the experiential dimensions of the issue. Rather than rely on technical calculations and analyses, citizens apply "cultural" logic or rationality, which is not necessarily inferior to

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[50] Fischer, *Citizens, Experts, and the Environment*, 123.

[51] Laurie Nadel, "Coast Guard Assesses Risks of Gas Plants," *New York Times* (Late Edition (East Coast)), 29 May 2005, 14LI.

[52] S. Laurence Paulson, "Promoting the Promise of LNG," *American Gas* (June 2005): 17.

[53] Fischer, *Citizens, Experts, and the Environment*, 125.

the technical reason applied by experts. Cultural rationality considers different aspects of the problem that are often neglected by the experts. It focuses on personal experiences of individuals, not depersonalized expert studies produced by strangers using empirical evidence and the scientific method.[54]

Stakeholders in the community perceive risk differently than scientists and engineers who study the technical issues. The engineers and scientists who are considered "experts" focus on quantifying the probabilities and technical risks, and often give little thought to the broader impact the project has on the community. They are typically focused only on the present and on risks associated only with their facility. In contrast, average citizens are most interested in the broad ramifications and care less about technical probabilities and risk assessments.[55] Unlike the engineers, members of the community are also more apt to be influenced by a historical perspective and memory of experiences they view as similar.[56]

Comprehensive analyses performed by the scientists and engineers produce risk estimates to demonstrate the probability of experiencing an event with catastrophic consequences is statistically remote. They typically conclude the facility presents an "acceptable risk."[57] However, if people believe the event is even remotely possible, such studies are not likely to address the public's fear.[58]

In some communities the citizens simply refuse to accept technical analyses produced by the risk experts.[59] In response, experts strive to produce additional risk studies and technical data. But regardless of the level of effort or amount of supporting scientific documentation produced, it is extremely difficult to satisfy public concerns with

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[54] Alonzo Plough and Sheldon Krimsky, "The Emergence of Risk Communication Studies: Social and Political Context," *Science, Technology, & Human Values* (Summer – Autumn 1987): 8.

[55] William Freudenburg and Susan Pastor, "NIMBYs and LULUs: Stalking the Syndromes," *Journal of Social Issues* (January 1, 1992): 54.

[56] Kennedy P. Maize and John McCaughey, "NIMBY, NOPE, LULU, and BANANA: A Warning to Independent Power," *Public Utilities Fortnightly* (August 1, 1992): 20.

[57] Fischer, *Citizens, Experts, and the Environment*, 126.

[58] Robin Gregory and Howard Kunreuther, "Successful Siting Incentives," *Civil Engineering* (April 1990): 73.

[59] Fischer, *Citizens, Experts, and the Environment*, 122.

technical assessments of the risk associated with a proposed LNG terminal.[60] These attempts sometimes make matters even worse.[61]

Though people on all sides of the issue are concerned about risk, the debate over the siting of LNG import terminals is as much about trust in the relationship between the community and the developer as it is about the perceived risk associated with the proposed terminal.[62] As with other types of hazardous facilities, the uncertainty associated with the consequences of a large accident at a LNG import terminal and the unknown threat or probability of terrorist attack cause significant concern in the local community. Given this uncertainty and the presence of many other difficult siting issues, trust and confidence between the community and the developers is crucial. However, it seems this social trust is often missing.

In this context, social trust is defined as a person's expectation that other people or institutions involved in the siting process can be relied upon to act in a manner that is competent, predictable, and caring.[63] To develop trust in an individual or institution, the community must be vulnerable to the actions the individual or institution may take. In addition, members of the community must trust in the abilities and competencies of the institution and believe it has a caring attitude. Lastly, the institution must consistently meet the expectations of the community. Unfortunately, it takes so long to build trust that it may not be possible for developers to achieve a trusting relationship with the community in the relatively short amount of time afforded by the siting process.[64]

Since it is the health and safety of the community that is potentially at risk, a community will not likely accept a terminal unless it is confident decision makers share their concerns, are competent, and will act fairly. In spite of this, many experts remain convinced they can win public confidence by presenting scientific facts and results derived from complicated studies.

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[60] Maize and McCaughey, 21.

[61] Fischer, *Citizens, Experts, and the Environment*, 127.

[62] Roger Kasperon, Dominic Golding, and Seth Tuler, "Social Distrust as a Factor in Siting Hazardous Facilities and Communicating Risks," *Journal of Social Issues* 48, no. 4 (January 1, 1992): 175.

[63] Ibid., 169.

[64] Ibid., 178.

The probabilities developed by the experts and associated with the threats and events that create the greatest concern have a limited degree of precision. As a result, technical specialists may be giving more credence and weight to the assessments than they deserve. In addition, the experts must often make value judgments and equate injuries and deaths with a monetary cost in order to calculate the risks or consequences. Though the technical experts likely believe their results are unbiased and scientific, they may contain significant value judgments that are detected by members of the community. Like everyone else, scientists are human and subject to political and economic pressures. It is not difficult to imagine experts intentionally or unintentionally underestimating the risks.[65]

In summary, the siting of LNG terminals is a very complex issue. The consequences of a successful terrorist attack on a LNG tank ship or import terminal are debated by the "experts." This professional disagreement among members of the scientific community is exacerbating the public's discomfort and fear. With the exception of some areas in Texas and Louisiana that have extensive experience with LNG, communities are apt to be opposed to the introduction of new LNG import terminals in their "backyards." Additional scientific research, technical studies, and risk analyses are not likely to resolve this conflict.

[65] Freudenburg and Pastor, *NIMBYs and LULUs*, 54.

IV. ANALYSIS METHODOLOGY

"Better defenses means more fences, more intrusion alarms, increased redundancy at the most vulnerable points in the electrical transmission grid, our gas pipelines, and so forth. If one transmission line or pipeline is knocked out, others should be available to handle the load."

- Response from Robert Kupperman, then Chief Scientist of the U.S. Arms Control and Disarmament Agency, provided for interview conducted in 1978[66]

A. RESILIENCY VS. PROTECTION

Critical infrastructures are vital to the security, economic prosperity, and quality of life in the U.S.[67] Though much of the critical infrastructure in the United States is highly efficient, certain sectors exhibit signs of aging, geographic concentration, or overstress by high demand.[68] These traits tend to exacerbate the impact of a failure, regardless of whether it is caused by the malicious intent of a terrorist or a natural disaster.

The establishment of national policy regarding the importance and protection of critical infrastructure started during the Cold War with plans to ensure continuity of our government in the event of a nuclear attack. An Executive Order issued in 1996 acknowledged that some national infrastructure is vital to the defense and economic security of the U.S. and created the President's Commission on Critical Infrastructure Protection. Based on the recommendations of the Commission, a National Goal was established to achieve the ability to *protect* the nation's critical infrastructures from intentional acts by 2000.[69] Efforts to meet this goal primarily focused on cyber threats and information networks.

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66 "Terrorism: Why U.S. Is Vulnerable," *US News & World Report*, 6 March 1978, 66.

67 *USA PATRIOT Act of 2001*, Sec. 1016, Public Law 107-56, 107th Cong., (26 October 2001) <http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=107_cong_public_laws&docid=f:publ056.107> (Accessed 6 February 2007).

68 Homeland Security Advisory Council, "Report of the Critical Infrastructure Task Force," January 2006 < http://www.dhs.gov/xlibrary/assets/HSAC_CITF_Report_v2.pdf >, 12 (Accessed 30 January 2007).

69 Presidential Decision Directive 63, "Critical Infrastructure Protection," 22 May 1998 <http://www.fas.org/irp/offdocs/pdd/pdd-63.htm> (Accessed 28 November 2006).

The attacks on September 11, 2001, generated unprecedented interest in the need to protect critical infrastructure. In February 2003, the White House published a national strategy for the physical protection of critical infrastructures. The Under Secretary for Information Analysis and Infrastructure Protection in the Department of Homeland Security was charged with the responsibility of assessing the vulnerabilities of the critical infrastructures in the U.S. and developing a comprehensive plan for securing them.[70]

To date, the primary focus has been on protecting critical infrastructure by mitigating the terrorist threat. Homeland Security Presidential Directive (HSPD) 7 specifically states its purpose is to identify and prioritize critical infrastructure and protect it from terrorist attacks.[71] This narrow view differs from the "all-hazards" approach emphasized by DHS. As demonstrated in 2003 by the power blackout in the Northeast and by the widespread destruction caused by Hurricanes Katrina and Rita in 2005, the consequences of failures caused by threats other than terrorism can also have devastating consequences.

In 2005, the Homeland Security Advisory Council formed the Critical Infrastructure Task Force (CITF) and asked it to provide recommendations to advance national critical infrastructure policy and objectives. The CITF focused on ensuring optimal delivery of critical infrastructure services in an "all-hazards environment" and reducing the consequences and disruption caused by damage or loss.[72]

The majority of critical infrastructure, including the LNG import terminals and natural gas pipelines comprising the natural gas supply and distribution network, is owned and operated by several different entities within the private sector. The CITF held numerous discussions with private-sector stakeholders and determined that businesses are more likely to make investments to provide continuity of operations than they are to expend resources in an attempt to simply protect infrastructure.[73] Industry's economic

70 *Homeland Security Act of 2002*, Sec. 201, Public Law 107-296, 107th Cong., (25 November 2002) <http://www.whitehouse.gov/deptofhomeland/bill/> (Accessed 28 November 2006).

71 Homeland Security Presidential Directive/HSPD-7, "Critical Infrastructure Identification, Prioritization, and Protection," 17 December 2003 <http://www.fas.org/irp/offdocs/nspd/hspd-7.html> (Accessed 28 November 2006).

72 Homeland Security Advisory Council, "Report of the Critical Infrastructure Task Force," i.

73 Ibid., 5.

interest and desire to sustain operations in the face of threats or unanticipated disruptions is in alignment with the federal government's growing desire to improve the resiliency of critical infrastructure.

It is not possible to protect every potential target from every conceivable threat. Though prevention efforts are necessary, they alone are not sufficient. The CITF concluded that policies and strategies should focus on *resilience* instead of *protection*. Resilience is defined as the capability of a system to maintain its functions and structure in the face of internal and external change and to degrade gracefully when it must.[74]

B. INDIVIDUAL COMPONENTS VS. NETWORKS

Like other critical infrastructure sectors, the natural gas storage and distribution infrastructure did not evolve as a random, unstructured arrangement of import terminals, storage facilities, and pipelines. Instead, the infrastructure, which is owned and operated by various companies, was developed over time in an optimal manner to maximize efficiency, economies of scale, and profit.[75]

To properly determine the resiliency of critical infrastructure, the entire sector must be considered as a system. It is not enough to simply isolate and evaluate separate LNG import terminals, pipelines, or power plants. All of the individual components must be assessed together as a system.

Typically, vulnerability and risk assessments are specific to just one particular piece, or component, of the infrastructure. Since the vast majority of our critical infrastructure is privately owned and operated, this approach seems to make sense. Each owner or operator is responsible for their components. However, when federal, state and local governments are attempting to allocate the limited resources available for security and protection, the optimal distribution of resources can only be achieved if one understands the relationships between the different components and their relative importance to the overall health of the system. Rather than making incremental

[74] Homeland Security Advisory Council, "Report of the Critical Infrastructure Task Force," 5.

[75] Paul Parfomak, *Vulnerability of Concentrated Critical Infrastructure: Background and Policy Options*, CRS Report for Congress (Washington, D.C.: GPO, 2005), 9.

improvements in the security of all individual components, the entire system can be modeled and analyzed so that available resources can be distributed optimally.

With increasing resiliency as the goal, it is important to understand how these components are interconnected and what impact a failure or attack on one component has on the others. To accomplish this, one must consider the various sectors of critical infrastructure as "networks." The individual assets or components, identified as "nodes," in the network are connected to each other via "links."[76] In network modeling, nodes can represent any component of interest and will vary depending on the level of detail and the purpose or intent of the model. They may be chemical facilities, ports, rail hubs, airports, or telecom hotels. The links typically represent some type of relationship or connection between the nodes. The nodes with the most links are the most interconnected and serve as "hubs." They are especially important because damage to the network is often maximized by their removal.

For natural gas supply and distribution, network resiliency is measured by its ability to keep supplying and distributing natural gas in spite of damage to pipelines, LNG import terminals, storage, and other gas sources. Evaluating the resiliency of a network includes the identification and assessment of bottlenecks, points of maximum consequences, and damage tolerance. In addition, interdependencies of network components, impacts of failures, and risk mitigation possibilities are also considered.

C. NETWORK MODELING

The natural gas supply and distribution network consists of interconnected import terminals, processing facilities, underground storage areas, and pipelines. For this study, the flow of natural gas to twenty four states in the eastern half of the United States was considered. The pipelines connecting these states carry natural gas from the Gulf of Mexico to markets in the Midwest and along the East coast, accounting for approximately 75% of the nation's total natural gas flow.

[76] Lewis, *Critical Infrastructure Protection*, 78.

The data used to model the networks were obtained from the FERC and the EIA, which is responsible for providing statistics and information relevant to energy production and demand.[77]

1. Network Variations

To demonstrate the merit of using network theory to predict the impact new LNG import terminals will have on the resiliency of the natural gas supply and distribution infrastructure, three permutations of the network are modeled and analyzed.

a) "Total Network" – The Total Network contains all existing, proposed, and approved LNG import terminals.[78] However, as discussed in Chapter II, Section C, only a few of the new terminals will likely ever be built.

b) "Dispersed Network" – The Dispersed Network includes all existing LNG import terminals and eight of the proposed or approved terminals located in different geographic areas along the East and Gulf coasts.

c) "Concentrated Network" - The Concentrated Network contains all existing LNG import terminals and eight of the new terminals proposed or approved for either Texas, Louisiana, or Mississippi.

Each permutation is modeled using Network Analysis 4.0.[79] This software program allows the user to define any network as a system of interconnected nodes and links, each with its own value or weighting relative to the other nodes and links.

Each state is considered as a node. All of the natural gas pipelines that transport the gas between two adjacent states are combined and modeled as one link joining the two state nodes. Import terminals are modeled as source nodes and supply natural gas to the network. Each state also has a "sink" node attached to it to represent its own natural gas demand.

[77] Energy Information Administration, *Mission and Overview*, 2 October 2006, <http://www.eia.doe.gov/neic/aboutEIA/quickfacts.html> (2 October 2006).

[78] This variation of the network includes the existing, proposed, and approved terminals in October 2006. For a current list of LNG terminals and their status, see: <http://ferc.gov/industries/lng.asp#howmany>.

[79] The software and user guide are available at no cost from the Center for Homeland Defense and Security and can be accessed at https://www.chds.us/?research/software&d=list.

2. States

Since the majority of the increase in demand is expected to occur over the next twenty years, the anticipated demand in 2017 was modeled.[80] The predicted maximum peak consumption per day for each state in 2017 was determined by dividing each state's annual consumption in 2004 by 365 to get the average daily demand, adjusting it to model the maximum seasonal demand, and applying a factor to represent the predicted growth.[81] Maximum seasonal demand was derived by analyzing monthly consumption data.[82] The demand for natural gas was 43% greater in January than the monthly average. Accordingly, the daily demand, or consumption, for each state was increased by 43% to represent its peak daily demand. In addition, the maximum demand for each state was further increased to model future growth predicted by the EIA, which ranged from 0.5% to 1.3% per year.[83] Table 1 presents the peak demand expected for each state in 2017.

The natural gas flow through each node is modeled in Network Analysis 4.0 as an "Economic Loss" measured in millions of cubic feet per day (MMcf/d). To prevent the software from artificially restricting flow, the capacity of each state node was modeled as the sum of the maximum flows into the node.

[80] Energy Information Administration, "Annual Energy Outlook 2006," 85.

[81] Energy Information Administration, "Natural Gas Consumption by End Use," <http://tonto.eia.doe.gov/dnav/ng/ng_cons_sum_dcu_nus_a.htm> (Accessed 29 September 2006).

[82] Ibid.

[83] Energy Information Administration, "Annual Energy Outlook 2006," 85.

Table 1. Natural Gas Demand for Each State

State	Maximum Daily Demand in January 2017 (MMcf/d)
AL	1,841
CT	696
FL	3,480
GA	1,865
IL	4,250
IN	2,341
KY	1,002
LA	6,075
MA	1,593
MD	847
ME	310
MS	1,337
NC	987
NH	262
NJ	2,734
NY	4,819
OH	3,664
PA	3,095
RI	311
SC	728
TN	1,096
TX	18,571
VA	1,218
WV	536

3. Pipelines

Pipelines are the links between the nodes. The capacity and direction of natural gas flow was determined by analyzing data obtained directly from the EIA. The capacities of all major interstate pipelines were summed to determine the maximum flow capacity between each pair of adjacent states. The results are displayed in Table 2.[84] Like nodes, the flow through each link is modeled in Network Analysis 4.0 as an "Economic Loss" in units of MMcf/d.

It should be noted that this is only an approximation of the connectivity of the nodes, as each link really represents all of the significant natural gas pipelines that cross the border between each pair of adjacent states. For instance, the flow from New York to Connecticut is almost divided equally between two pipelines. Similarly, the majority of the natural gas transported from Pennsylvania to New Jersey is delivered via three main pipelines, with one of them responsible for nearly 50% of the flow. Alabama and

[84] James Tobin (Natural Gas Industry Analyst, Energy Information Administration), email to author, 29 September 2006.

Tennessee each have six pipelines with capacities greater than 500 MMcf/d that carry natural gas across the border from Mississippi.

Table 2. Direction and Capacity of Pipeline Flow

Direction of Flow		Maximum Flow (MMcf/d)
From	To	
AL	FL	3,354
AL	GA	6,112
CT	RI	760
GA	SC	3,885
IL	IN	6,199
IN	OH	4,160
KY	IL	1,544
KY	IN	2,406
KY	OH	3,843
KY	WV	2,663
LA	MS	14,135
MD	PA	2,050
ME	NH	600
MS	AL	12,907
MS	TN	9,913
NC	VA	2,870
NH	MA	400
NJ	NY	2,456
NY	CT	1,530
NY	MA	1,059
OH	PA	2,125
OH	WV	1,380
PA	NJ	5,247
PA	NY	550
RI	MA	385
SC	NC	3,692
TN	KY	12,581
TX	LA	3,826
VA	MD	3,280
WV	PA	4,040

4. LNG Import Terminals

The maximum natural gas supply, or daily "send out" capacity, for each proposed and existing LNG import terminal was obtained from FERC and is listed below in Table 3.[85] LNG import terminals are modeled as source nodes.

[85] Federal Energy Regulatory Commission, "Existing and Proposed LNG Terminals," <http://ferc.gov/industries/lng/indus-act/terminals/exist-prop-lng.pdf> (Accessed 29 September 2006).

Table 3. LNG Import Terminals

Name	Location	Send Out Capacity (Mmcf/d)	Concentrated Network	Dispersed Network
El Paso - Southern LNG	Elba Island, GA	2,100	Existing	Existing
Southern Union - Trunkline LNG	Lake Charles, LA	2,100	Existing	Existing
Gulf Gateway Energy Bridge	Gulf of Mexico	500	Existing	Existing
Suez/Tractebel - DOMAC	Everett MA	1,035	Existing	Existing
Dominion - Cove Point LNG	Cove Point, MD	1,800	Existing	Existing
Cameron LNG - Sempera Energy	Hackberry, LA	2,600	X	X
Creole Trail LNG - Cheniere LNG	Cameron, LA	3,300		
Weaver's Cove Energy	Fall River, MA	800		X
Crown Landing LNG - BP	Logan Township, NJ	1,200		X
Cheniere/Freeport LNG Dev	Freeport, TX	4,000	X	X
Sabine Pass Cheniere LNG	Sabine, TX	4,000		
Cheniere LNG	Corpus Christi, TX	2,600	X	X
Vista Del Sol - ExxonMobil	Corpus Christi, TX	1,100		
Golden Pass - ExxonMobil	Sabine, TX	2,000		
Ingleside Energy - Occidental Energy	Corpus Christi, TX	1,000	X	
Sempra	Port Arthur, TX	3,000	X	X
Port Pelican - Chevron Texaco	Gulf of Mexico	1,600		
Gulf Landing - Shell	Offshore LA	1,000		
AES Battery Rock	Boston MA	800		
Safe Harbor Energy	Offshore NY	2,000		
Freedom Energy Center - PWG	Philadephia, PA	600		
AES Sparrows Point - AES Corp	Baltimore, MD	1,500		
Quoddy Bay	Pleasant Point, ME	2,000		X
Downeast LNG - Kestrel Energy	Robbinston, ME	500		
Gulf LNG Energy	Pascagoula, MS	1,300		
Casotte Landing - ChevronTexaco	Pascagoula, MS	1,300	X	
Broadwater Energy - Transcanada/Shell	Long Island Sound, NY	1,000		X
Calhoun LNG- Gulf Coast LNG Partners	Port Lavaca, TX	1,000	X	
Suez Calypso - Suez LNG	Offshore FL	0		
Bienville Offshore Energy Terminal	Gulf of Mexico	1,400		
Beacon Port Clean Energy Terminal	Gulf of Mexico	1,500	X	
Main Pass McMoRan Exp	Offshore LA	1,000		
Northeast Gateway - Excelerate Energy	Offshore MA	800		
Neptune LNG - Suez LNG	Offshore MA	400		

5. Storage

Approximately 7,500,000 MMcf of gas are stored in underground natural facilities, such as large salt domes and depleted reservoirs. Natural gas is added to these reserves from late spring until fall, when demand is relatively low, and accessed during winter months when demand peaks. Although LNG is stored in approximately 100 peak shaving plants, the total amount stored is less than 15% of that kept in natural underground storage.[86] These small LNG storage facilities are not included in these analyses.

[86] Energy Information Administration, "U.S. LNG Markets and Uses," <http://www.eia.doe.gov/pub/oil_gas/natural_gas/feature_articles/2003/lng/lng2003.pdf> (Accessed 9 January 2007), 11.

Of the twenty six states included in the network, fourteen have underground storage. The amount of natural gas stored in each of them in October of 2004 is shown in Table 4. It should be noted that with the exception of New York, which accounts for only 4% of the stored gas in the network, there is no storage in the Northeast.

The stored gas at each node could be lost as a "consequence" of a node failure or attack and is modeled as "other loss" for the corresponding state nodes in Network Analysis 4.0. The amount stored was converted to a daily average to provide consistency with the units of flow.

Table 4. Stored Natural Gas

State	Storage (MMcf)	"Daily" Storage (MMcf/d)
IL	936,941	2,632
PA	728,031	2,045
TX	574,578	1,614
LA	540,155	1,517
OH	533,056	1,497
WV	472,884	1,328
KY	218,741	614
NY	190,407	535
MS	140,609	395
IN	110,405	310
MD	61,352	172
AL	9,347	26
VA	7,223	20
TN	879	2

D. NETWORK ASSESSMENT

1. Hub Analyses

For each network variation, the structure and connectivity is evaluated and the general characteristics are examined. Critical nodes and links are identified based on their connectivity to other network elements. In addition, the effectiveness of investments to reduce the risk in each network is determined and compared. The optimal allocation strategy to achieve minimal risk in each network is established and the investment priorities are compared.

In Network Analysis 4.0, the "vulnerability" of a given component is defined as the probability of a fault, or the probability that the component will fail. The "risk" posed by a component's failure is the product of its vulnerability and "damage consequence."

Each component's damage consequence has a corresponding "elimination cost," which defines the investment necessary to secure the node or link and protect it from any damage or loss. Resources invested to protect an individual component reduce its vulnerability.

In this study, the investment necessary to protect each node and link and entirely prevent it from losing flow was assumed to be equal for all nodes and links and arbitrarily set at a value of ten monetary units. Similarly, for nodes that have natural gas storage, the investment required to perfectly protect the stored gas was also assumed to be ten monetary units.

The relationship between the resources invested in a component's elimination costs and the corresponding reduction in vulnerability is assumed to be linear. In other words, doubling the investment in a node will cut its vulnerability and the consequences of its loss in half. In reality, this is probably not true. More likely, the amount of additional security that can be achieved with each dollar spent continually diminishes at some exponential rate or the relationship between the elimination costs and vulnerability is discontinuous, or "stepped." However, since this study is only intended to compare the network permutations to show how they differ, assuming a linear relationship between elimination costs and consequences will not impact the results.

Presuming any network can be made more secure by making investments and purchasing improvements that reduce the probability of failure and vulnerability of the individual nodes and links, Network Analysis 4.0 prescribes the investment strategy that produces the lowest possible network risk. The optimal resource allocation strategy is determined by letting it "emerge" from the network. It begins by initially distributing the available budget equally between the links and nodes. A "donor" node or link is then randomly selected and some of its portion of budget is reinvested in a randomly selected "recipient" node or link. If the total network risk is not decreased, the dollar is returned to the donor; otherwise, the recipient keeps it. This organizing principle is repeated until the pattern representing the best allocation strategy emerges.[87]

[87] Lewis, *Critical Infrastructure Protection,* 153.

The hub analyses provide useful information about each network's structure and help identify the critical components. However, the value of nodes and links in the analyses are directly related to their maximum capacity. A hub analysis does not consider the optimal flow in each pipeline necessary to best satisfy the demand of all nodes in the network. In performing a hub analysis, Network Analysis 4.0 assumes damage to a pipeline with a high maximum capacity is a greater loss than damage to a smaller pipeline, even though the smaller pipeline may actually have more flow than the larger pipeline. In order to evaluate the resiliency of a supply and distribution network, it is also necessary to consider the impact of damage on various network components.

2. Damage Analyses

To facilitate this study, a model was created in Microsoft Office Excel 2003 to simulate the Concentrated and Dispersed Networks. Individual formulas were developed for the nodes in each network to mathematically represent the physical constraints of network flow.

The Solver function in Microsoft Excel was then used to determine the optimal network flow by adjusting the "consumption," or supply, of each node and the flow in each link.

The following constraints were modeled for each network:

- *Node* $Flow_{in} \leq$ *(Node* $Flow_{out}$ *+ Node Demand):* For each node, the sum of all natural gas flow "in" must not exceed the node's demand and the sum of all flow "out" of the node. In this manner, the conservation of mass is preserved at each node.
- *Node Consumption ≤ Node Demand:* For each node, the amount of natural gas supplied to each node is not allowed to exceed the node's demand. This does not consider the ability of some nodes to store natural gas. Permitting storage at the nodes would complicate the model significantly and is not necessary to demonstrate the efficacy of the technique and theory.

- *Node Consumption ≥ 0:* For each node, consumption, or supply, cannot be less than 0. A node cannot have "negative" consumption.
- *|Link Flow| ≤ Link Capacity:* For each link, the flow must not exceed its specified maximum flow capacity. This ensures that the natural gas flow in each pipeline does not exceed its physical limitations; however, unlike the hub analysis, the flow is permitted to go in either direction.

Ideal Flow Efficiency = Total of LNG Imports / Total Network Demand
Actual Flow Efficiency = LNG Supplied to Nodes / Total Network Demand

After the optimal flow for the network is established, damage to individual pipelines and import terminals is simulated by setting the corresponding flow capacities to zero. Flow degradation is assessed by evaluating the maximum possible flow in the "damaged" network and comparing it to the optimal flow in the undamaged, or "intact," network. Though solutions are not necessarily unique and more than one combination of pipeline flow may satisfy the constraints, the most severe damage scenarios are determined for each network by performing several analyses. As a result, the resiliency, or ability of each network to continue to supply natural gas and satisfy demand in the face of natural and man-made damages, is determined.

The maximum allowable pipeline flow, demand, and supply modeled in the damage analyses are different from the models used in hub analyses performed using Network Analysis 4.0. The values for each are presented with the results in Figures 20 and 21. This is necessary to accurately determine flow efficiency and satisfy the constraints. The damage analyses model the demand and optimal flow of natural gas in 2030, which experts predict must be satisfied by new LNG import terminals. In 2004, 650,000 MMcf were imported and current projections indicate 4,360,000 MMcf of LNG will be needed to meet the U.S. demand in 2030.[88] As a result, in 2030 the supply and distribution network in the U.S. will need to accommodate the difference, or 3,710,000

[88] Philip Budzik (Office of Integrated Analysis and Forecasting, Energy Information Administration), email to author, 8 December 2006.

MMcf of additional natural gas. Assuming it is distributed equally over the entire year, this will result in an additional flow of 10,421 MMcf/d.

Because the twenty four states modeled in the Concentrated and Dispersed Networks consumed three quarters of the natural gas imported in 2004, it is assumed these networks will need to accommodate 75% of the new flow, or 7,815 MMcf/d in 2030. This additional demand is distributed proportionally among the states based on a relative comparison of their individual demands in 2004. Similarly, the 7,815 MMcf/d of imported LNG is assumed to be distributed to the state nodes according to their relative import capacity.

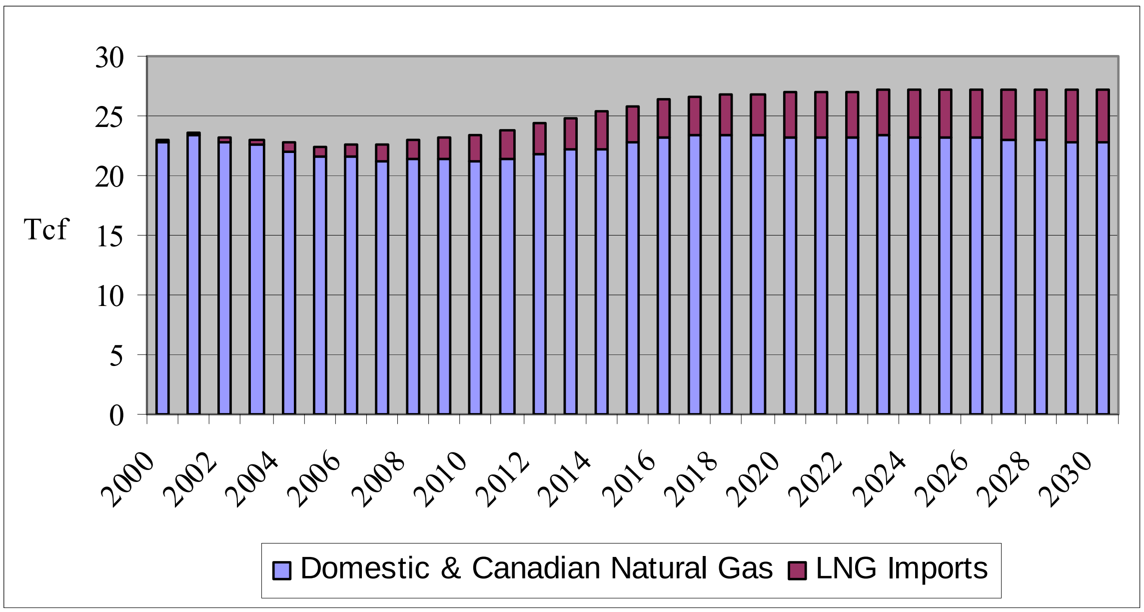

Figure 9. Total Annual Supply of Natural Gas in Trillion Cubic Feet (Data from the Energy Information Administration, "Annual Energy Outlook 2006" <http://www.eia.doe.gov/oiaf/archive/aeo06/aeoref_tab.html>).

The pipeline capacity is conservatively assumed to remain constant. No new pipeline construction is considered. As shown in Figure 9, the pipeline capacity needed to transport both the domestically produced natural gas and the gas imported from Canada is expected to remain relatively constant until 2030. Any existing excess capacity in the pipelines can be assumed available for transporting natural gas imported by new LNG terminals in the form of LNG. The excess capacity available, or assumed flow capacity, for each pipeline is the difference between its maximum capacity and average flow rate in 2004.

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V. RESULTS OF NETWORK ANALYSES

"We can site all the LNG we want in the Gulf, but it won't help people in New England." - senior FERC official[89]

A. NETWORK OBSERVATIONS

Graphical representations of the three networks studied in this work, Total, Dispersed, and Concentrated, are shown in Figures 10, 11 and 12, respectively. Each state has a yellow node, which represents the natural gas flow passing through the state and its natural gas storage, as applicable. The red node represents the natural gas demand for the state. The green nodes represent the existing and proposed LNG import terminals. Each of the figures contains a histogram in the lower left corner with the number of nodes with degree "g" (nodes having g links) plotted versus "g."

All three networks share some common traits. As shown by the histograms, the number of links is not uniformly distributed. Instead, in each network a small number of nodes have the majority of the links. Rather than exhibiting characteristics of a random network, the histograms indicate the presence of a "scale-free" network, which is a network which contains a few highly connected nodes.[90] The distribution of links in each network follows a power law where the probability of a node having a degree "g" is proportional to $(g)^{-P}$, where P is greater than 1. Though the "demand" node modeled for each state has a degree of only 1 and artificially increases total number of nodes in the network, the distribution of links still follows a power law if the demand nodes are not included, as shown in Figure 13.

Because most nodes in a scale-free network have less than the average number of links and a random attack on one of the nodes is not likely to hit one of the few, highly connected hubs, these networks are generally viewed as "fault-tolerant." That is, a random attack is not likely to take out the high-value hubs.[91] Though this provides some assurance for the reliability of the network under natural circumstances, terrorists are not

[89] Paul Parfomak, *Liquefied Natural Gas*, 13.

[90] Lewis, *Critical Infrastructure Protection*, 82.

[91] Ibid., 98.

likely to select targets at random. Consequently, it becomes even more important to identify and protect critical nodes and links.

Because the import terminals are "source" nodes, there can be no flow without them, and even though they have a degree of only one, they are especially important. In the network approach, these become high value targets where a successful attack has dire consequences. In addition, examination of the network reveals the importance of the pipelines linking Texas to Louisiana and Louisiana to Mississippi. Major pipelines split in Mississippi and branch off to the Midwest and South. Natural gas from the Gulf coast flows through Kentucky to underground storage in the Midwest and Northeast.

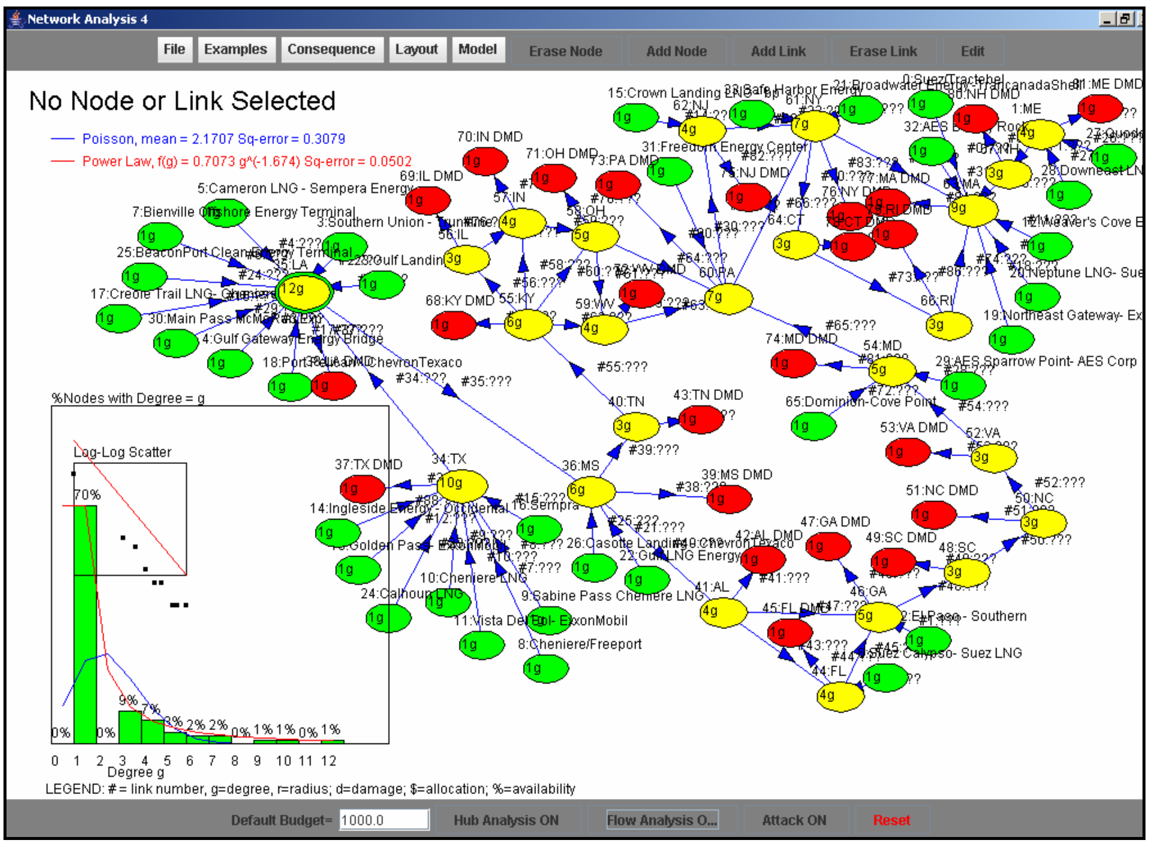

Figure 10. Graphic representation and histogram for the Total Network

In the Total Network, Louisiana and Texas are the most highly connected nodes, with degrees of 12 and 10, respectively. As such, they serve as hubs in the network and loss of either of these nodes would seriously impact the performance of the network.

As previously stated, it is estimated that only 25% of the LNG import terminals depicted in the Total Network will be constructed. Since further study of this network has limited practical application, additional analysis and discussion is dedicated to the analysis and comparison of the Dispersed and Concentrated Networks.

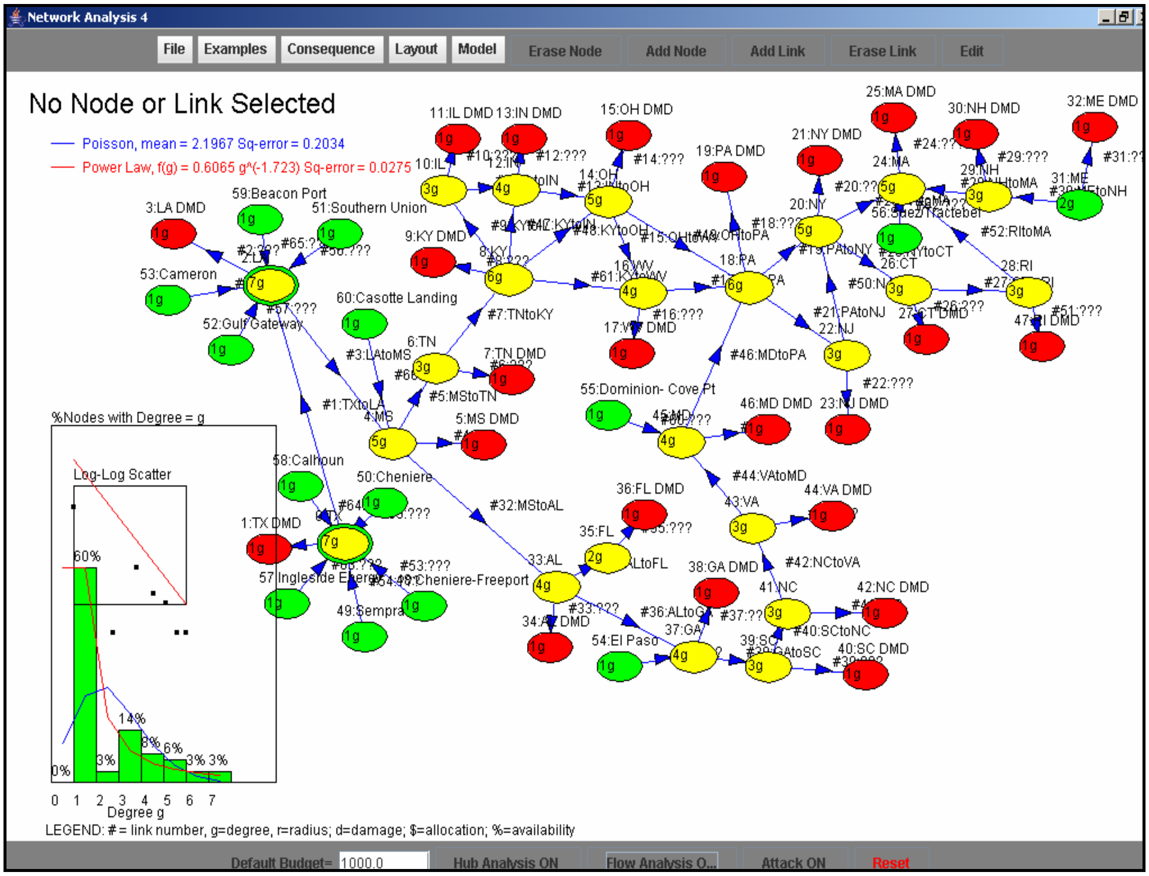

Figure 11. Graphic representation and histogram for the Concentrated Network

In the Concentrated Network, Texas and Louisiana are still the primary hubs, but with a degree of only seven. Though they appear to be of equal value based on their connectivity, the amount of flow each provides to the network must be considered. The five supply nodes attached to Texas supply 47% of the entire network's natural gas. Texas provides 73% more gas to the network than Louisiana's four supply nodes, but it is relatively isolated from the network. None of the natural gas provided by supply nodes linked to Texas can be transported and used to satisfy the demand of other nodes in the network unless it flows through Louisiana. Consequently, if the supply nodes of Texas are considered in addition to its own, Louisiana provides 75% of the entire network's supply. If the Louisiana state node is damaged or "eliminated," meaning flow through Louisiana is disrupted, the entire network must compete for the limited gas provided by the four remaining supply nodes connected to Massachusetts, Maryland, Georgia, and Mississippi.

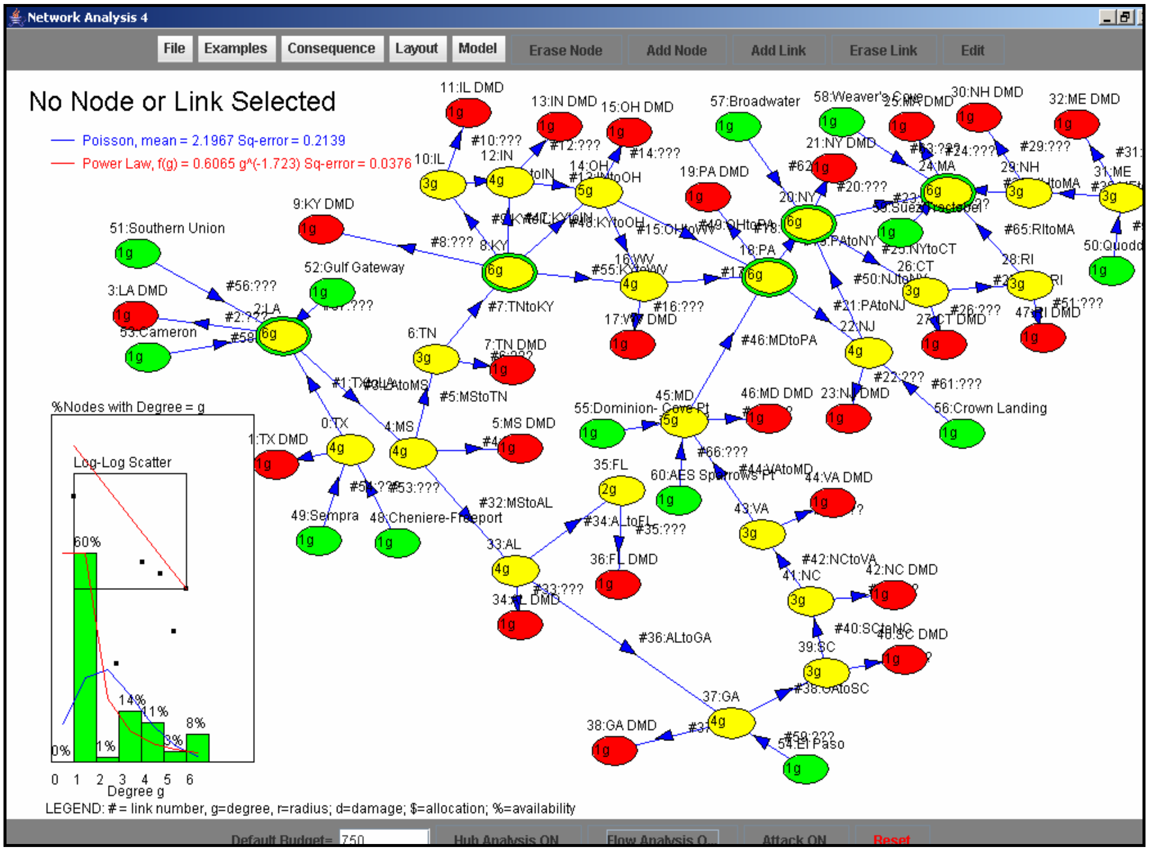

Figure 12. Graphic representation and histogram for the Dispersed Network

Though the individual capacity of each import terminal selected for each of the networks is unique, the total amount of LNG supplied to each network is nearly the same. The 23,635 MMcf/day supplied in the Dispersed Network is only 3% less than the amount provided in the Concentrated Network. The Dispersed Network has five nodes with a degree of six and, based on the histogram, is also scale-free. Relative to the other nodes in the network, Louisiana still has a high degree. However, in comparison to the Concentrated Network, it is much less critical.

The supply nodes linked to Texas provide only 30% of the of the Dispersed Network's entire natural gas supply. If its own three supply nodes are considered together with natural gas received from Texas, Louisiana is responsible for providing

51% of the Dispersed Network's supply. Though this is, indeed, a significant amount, it is 33% less than the amount provided by Louisiana in the Concentrated Network.

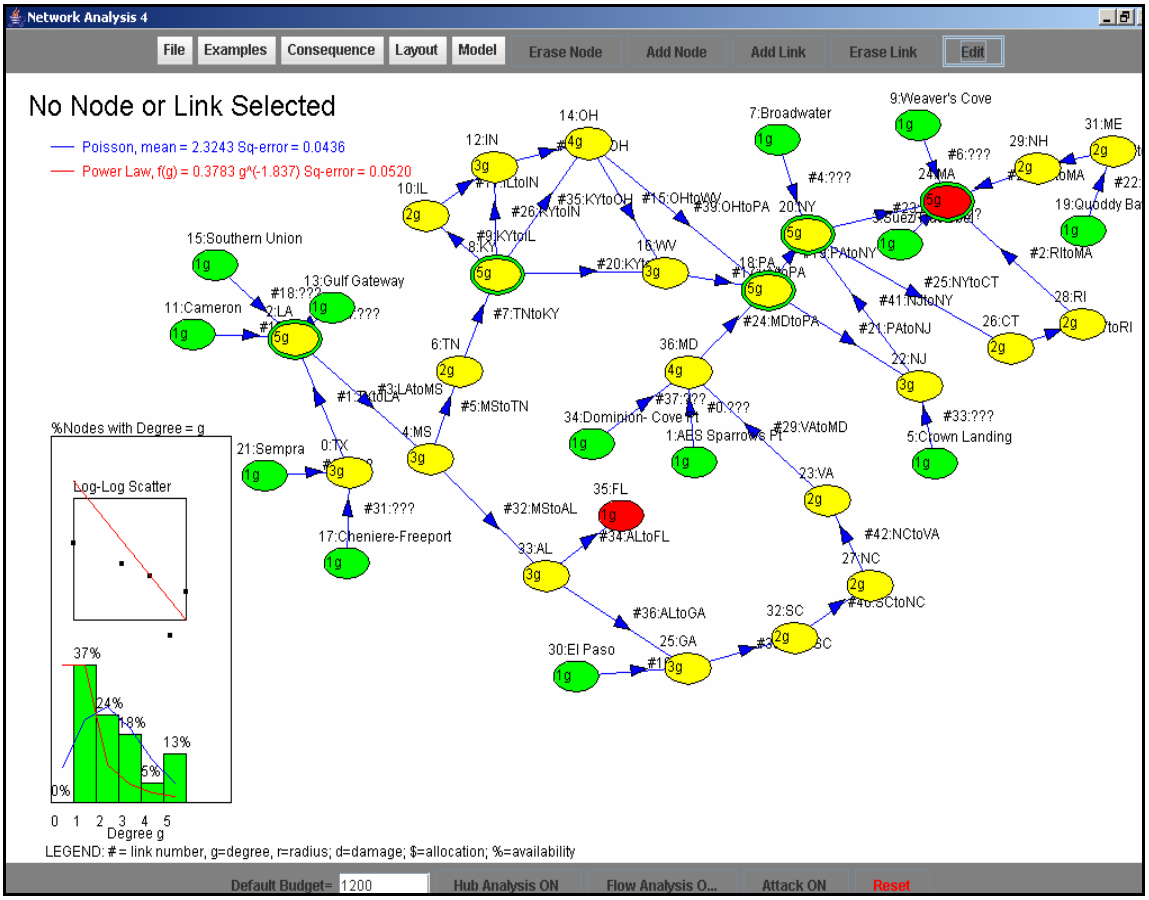

Figure 13. Histogram of the Dispersed Network without individual demand nodes still indicates presence of a "scale-free" network.

In summary, the nodes with the greatest degree of connectivity are the hubs. Knowledge of the hubs is useful, but does not tell us much about the value of supply nodes because they have only one link and may be undervalued. We can derive qualitative results, but knowledge of demand, supply, and flow can be used in a hub analysis to obtain quantitative assessment of flow and the optimal resource allocation to reduce network risk.

B. HUB ANALYSES

The result of the hub analyses of the Total Network are presented in Figure 14. A few investments carefully targeted to protect some of the most valuable nodes dramatically reduce overall risk to the network. Investing only 20% of the sum of all elimination costs for all nodes and links eliminates 80% of the "overall" network risk, which is represented by the curve for "Flow and Storage Combined" and considers both network flow and stored natural gas. However, if the goal is to only secure network flow, the same reduction in risk can nearly be achieved by investing only half as much. If properly allocated, a 13% investment can fund elimination costs and improve the availability of critical nodes such that 79% of the risk to network flow is eliminated.

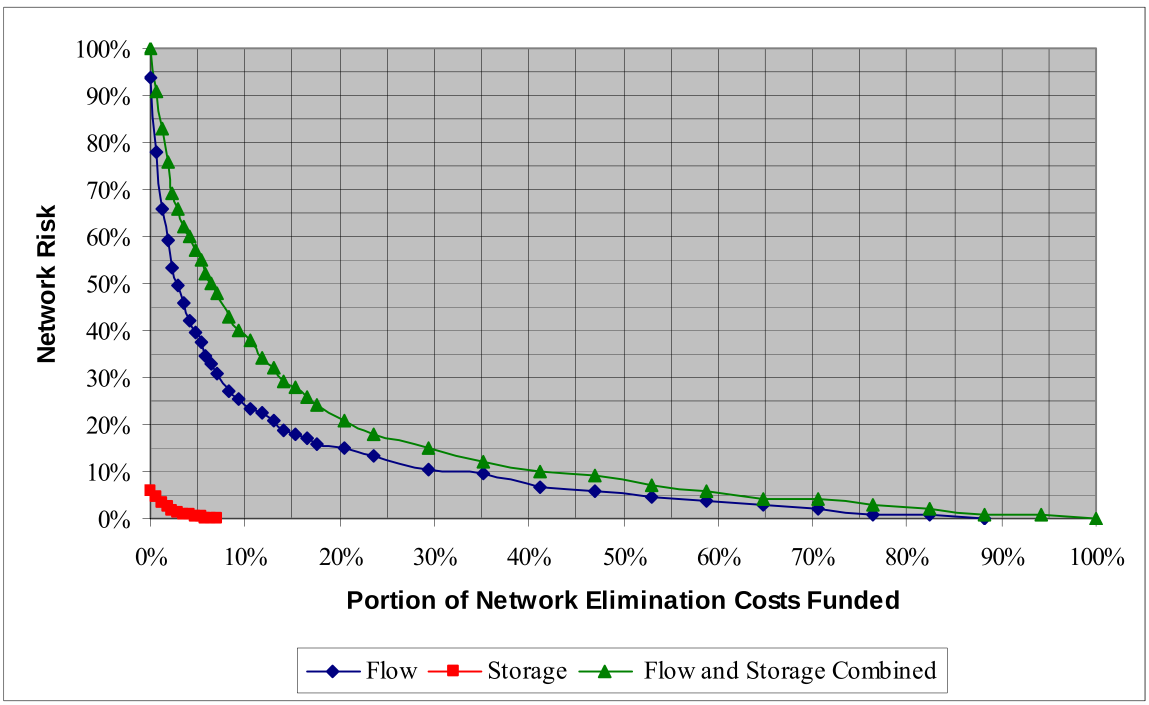

Figure 14. Hub Analysis Results for the Total Network

Of course, in order to be effective, the investments must be made to secure the appropriate nodes and links. Network Analysis 4.0 determines the optimal investment strategy for any given budget. As an example, Figure 15 demonstrates an investment of 100 arbitrary monetary units, a fraction of the total amount necessary to completely secure all nodes and links, will reduce by nearly half the risk to the network's flow and storage. To accomplish this, the $100 budget is allocated as shown in the bar chart at the bottom of Figure 15 and split evenly between Texas, Louisiana, Mississippi, Kentucky and Pennsylvania, which are represented by nodes 34, 35, 36, 55 and 60, respectively.

As discussed in Chapter IV, for the purpose of this study the investment necessary to protect each node and link and entirely prevent it from losing flow was assumed to be equal for all nodes and links and, for the sake of simplicity, set at a value of ten arbitrary monetary units. Similarly, for each node that stores gas, the investment required to perfectly protect the stored gas was also assumed to be ten monetary units.

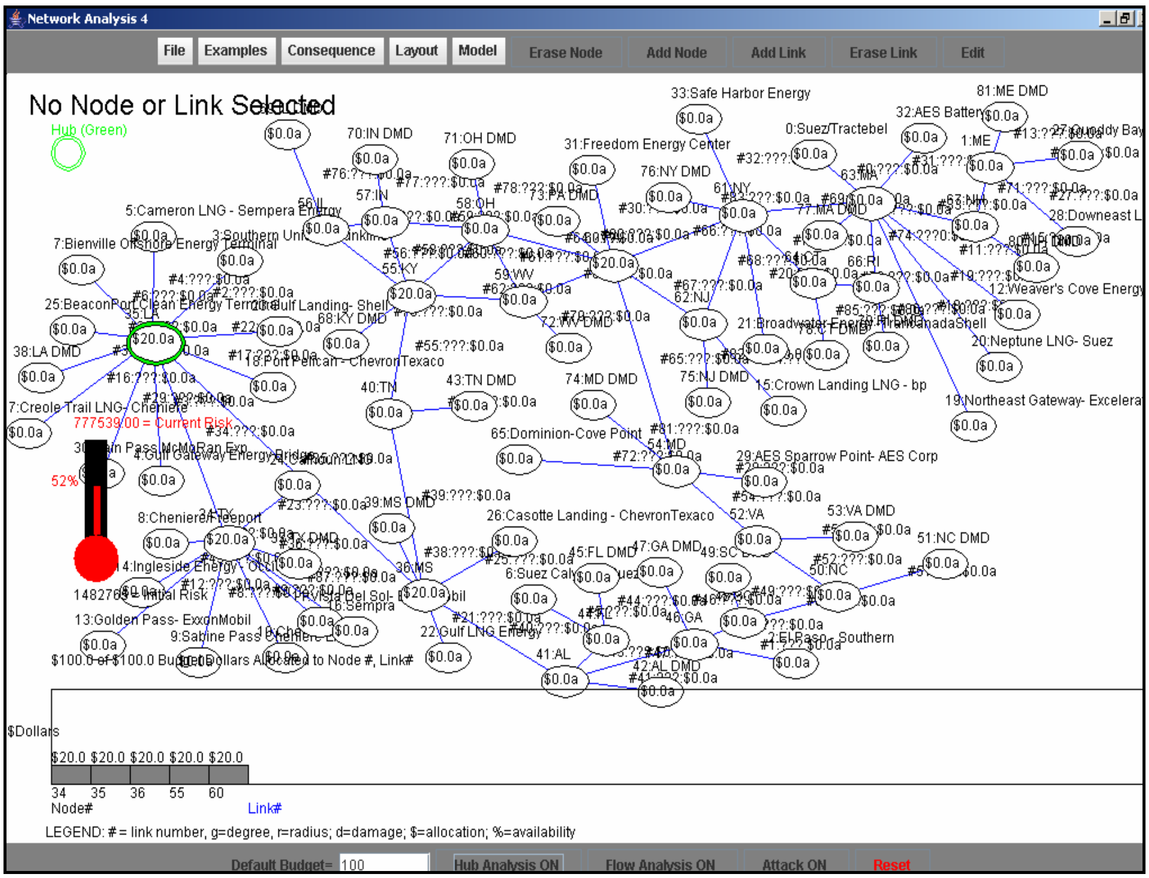

Figure 15. Allocation Strategy for Budget to Reduce Combined Risk in Total Network

The results for the Concentrated and Dispersed Networks are presented in Figures 16, 17, and 18. The difference in the return on investment between the two networks is negligible. Based on the hub analyses, there is no apparent advantage of one network over the other. Though the optimal resource allocation strategies for the two are different, nearly identical reductions in overall risk can be achieved for equivalent levels of investments to fund elimination costs. It is important to note that these results assume that the risks can be eliminated and that the elimination costs are essentially identical. A more careful analysis would likely reveal that such costs are dramatically different between the nodes in the different networks.

The similarity between the results for the different networks may initially seem surprising; however, with the exception of just four supply nodes and links, the Dispersed and Concentrated Networks are, in fact, the same. In addition, the amount of gas the four nodes supply, which determines the consequence and risk associated with their loss, are nearly identical for each network.

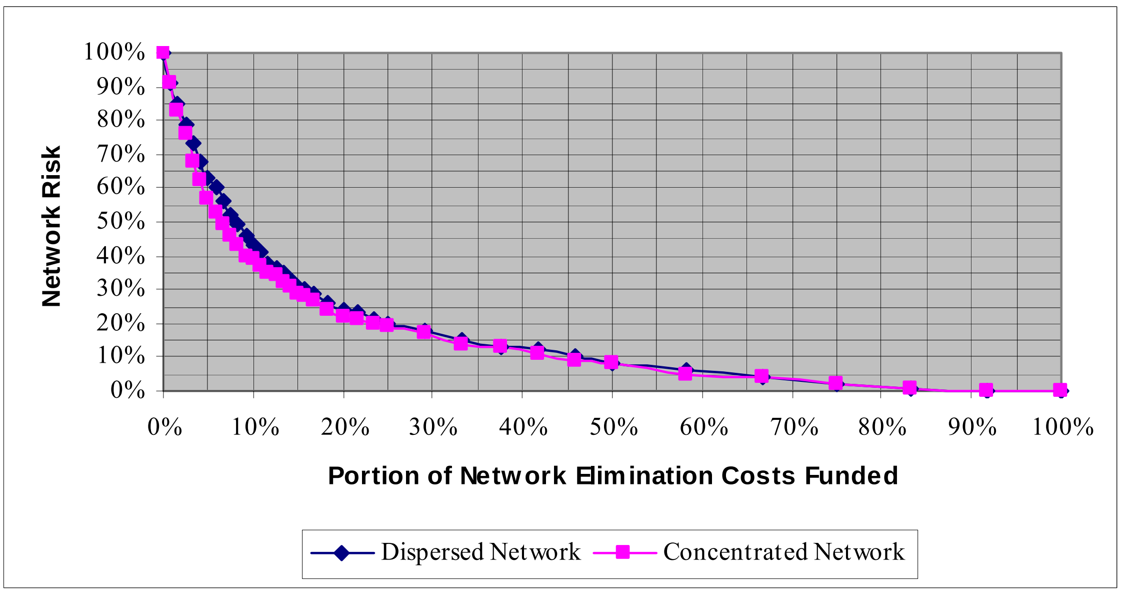

Figure 16. Relative Cost to Protect Natural Gas Flow

Like the Total Network, the return on investments to protect the flow of natural gas in the Concentrated and Dispersed networks is not linear. If allocated properly, investing only 10% of the cumulative elimination costs of all nodes and links improves network availability enough to eliminate 55% of the risk, as shown in Figure 16. Though the risk can be significantly reduced with relatively small investment, the return does diminish quickly with each subsequent dollar spent. Elimination of the last 10% of network risk will cost as much it costs to eliminate the first 90% of risk.

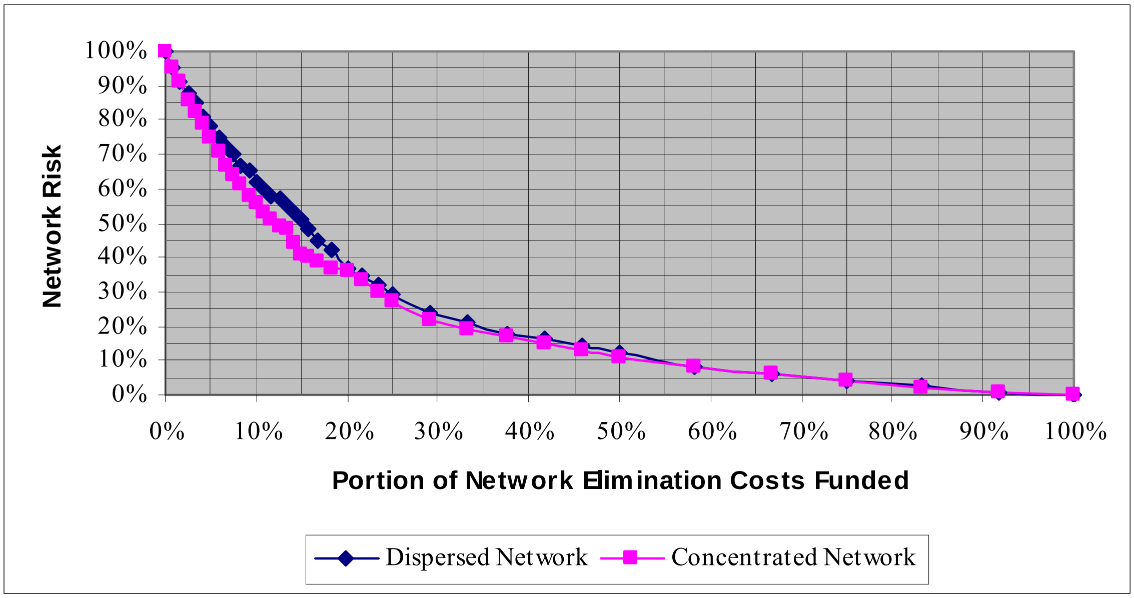

Figure 17. Relative cost to protect natural gas flow and storage

Though investments made to protect natural gas stored in various nodes within the network do not produce the same return as those made to ensure flow, they are still favorable. For either of the networks, investing approximately 25% of the total elimination cost for the fourteen nodes with stored gas reduces the risk to the stored gas by 50%.

The hub analyses of the Concentrated and Dispersed Networks demonstrate a given budget achieves nearly identical risk reductions for each of them, but the optimal allocation strategy to achieve the reduced risk are different in each network. Table 4 contains a relative ranking of nodes and links for each network. The order in which the nodes and links should receive funding varies with the network and the goal of the investment. For instance, if the budget is intended to reduce the risk to stored gas, then Pennsylvania is the first node to receive funding. However, if the goal is to protect flow or reduce the overall risk to either of the networks, different nodes should be protected. Texas is the first node to be funded in the Concentrated Network, but only receives funding in the Dispersed Network after ten other nodes have been secured and when risk has already been reduced more than 50%.

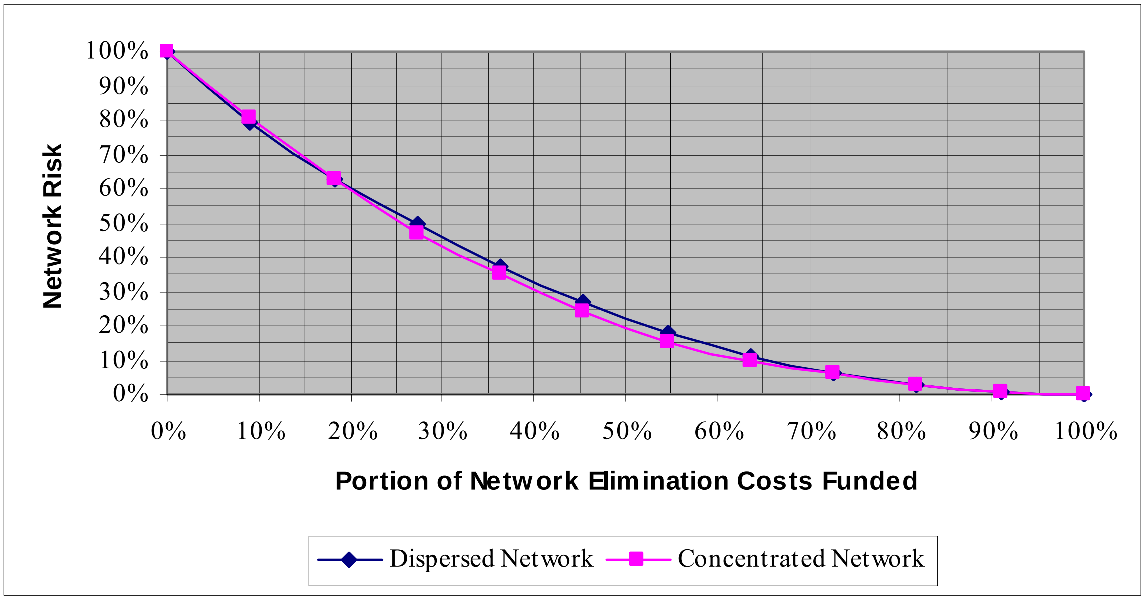

Figure 18. Relative cost to protect stored natural gas

It should be noted that the nodes with the most links are not necessarily the first nodes that should receive funding. Referring back to Figure 11, Louisiana had a degree of seven and was one of the most connected nodes in the Concentrated Network. Though Mississippi and Kentucky have fewer links, the maximum potential natural gas flow into them is greater. As a result, reducing the risk to gas flowing into Mississippi and Kentucky is more important to the overall risk to the network.

Though these results demonstrate it is possible to determine relative differences in the risk and vulnerability of various network configurations, the hub analysis algorithm used in Network Analysis 4.0 has two limitations when applied to the LNG supply and distribution network.

First, the value of each node and link in these analyses is based on their maximum capacity, rather than the actual or optimal flow rate. Assuming the connectivity of two different nodes is equal, damage to the node with the highest maximum flow capacity will always be considered a greater loss in a hub analysis, regardless of the actual flow in the node. The same is true for links.

Table 5. Relative Ranking of Nodes and Links

	Protect Flow		Protect Stored Natural Gas		Protect Overall Loss (Flow and Stored gas)	
Priority	Dispersed	Concentrated	Dispersed	Concentrated	Dispersed	Concentrated
1	KY	TX	PA	PA	KY	TX
2	MS	MS	LA	TX	PA	LA
3	LA	KY	IL	LA	LA	KY
4	PA	LA	OH	IL	MS	MS
5	AL	PA	TX	OH	AL	PA
6	OH	AL	WV	WV	OH	AL
7	IN	OH	KY	KY	IN	OH
8	MD	IN	NY	NY	TX	IN
9	GA	GA	MS	MS	MD	GA
10	TN	TN	IN	IN	MD	TN
11	TX	MD	MD	MD	GA	WV

Secondly, the algorithm favors hubs over links when determining the optimal resource allocation strategy. The cost of losing a node is determined by taking the damage consequences entered by the user and increasing them by a factor equal to the degree of connectivity of the node. However, the damage value of a link is always equivalent to the damage consequences, as defined by the user when modeling the network. As a result, a link with a user-defined damage consequence of 1000 MMcf/d will be less valuable than a node that is linked to three other nodes and has a damage consequence of only 400 MMcf/d (total damage value of 3 x 400 MMcf/d = 1200 MMcf/d).

The results of the hub analyses help identify critical nodes and links and provide useful information about the structure of each network configuration. However, the ability of each network to supply natural gas and meet the demands of the individual states when its nodes or links are attacked must also be considered.

C. DAMAGE ANALYSES

To assess the effect of damage, the optimal flow of the "intact" Concentrated and Dispersed networks must first be established. Once the optimal network flows are understood, the impact of damage to individual components can be determined. The damage analyses will demonstrate the advantages of the Dispersed Network over the Concentrated Network.

The optimal flow distribution for the Concentrated and Dispersed Networks are presented in Figures 19 and 20. Though the LNG is imported differently, each network is able to distribute it efficiently through existing pipelines and achieves a maximum possible flow efficiency of just slightly less than 100%. In the Concentrated Network, Texas (TX) is unable to accommodate its entire share of the imports and still satisfy the constraints of the problem. The maximum the Texas node can accommodate is 3,512 MMcf/d, which satisfies 100% of its own demand (2,202 MMcf/d) and maximizes the flow capacity of the link connecting Texas to Louisiana (1,310 MMcf/d); however, this is 183 MMcf/d, or 5%, less than the proportionate amount allocated to it. Similarly, Maine is unable to accommodate 39% of its entire share, or 256 MMcf/d, in the Dispersed Network.

Though there are many solutions that satisfy the constraints and achieve the maximum flow efficiency for each scenario studied, the results in Figure 20 highlight an interesting consequence that may arise when supply is concentrated in one region of the country. Though the flow efficiency for the entire network is 97.7%, the states closest to the import terminals supplying the network are satisfied while the nodes representing Maine and New Hampshire, which are at the end of the supply chain, receive no natural gas and have none of their demand satisfied, as shown in the "% Demand Satisfied" column.

Nodes	Supplied	Demand	Import	% Demand Satisfied	% Pipe Capcity Used	Link Name	Flow	Assumed Flow Capacity	from	to
TX	2,202	2,202	3,512	100.0%	100.0%	**tx1**	1310.0	1310	TX	LA
LA	717	720	2,134	99.5%	46.4%	**la1**	2726.9	5873	LA	MS
MS	155	159	414	97.9%	5.9%	ms1	332.4	5631	MS	AL
AL	215	218	0	98.5%	62.3%	**ms2**	2653.2	4258	MS	TN
FL	409	413	0	99.2%	28.4%	al1	409.4	1442	AL	FL
GA	218	221	669	98.5%	11.0%	al2	-292.1	2648	AL	GA
SC	89	92	0	96.5%	12.1%	ga1	159.0	1314	GA	SC
NC	123	126	0	97.4%	5.5%	sc1	70.1	1275	SC	NC
VA	153	156	0	97.9%	4.9%	nc1	-53.0	1088	NC	VA
MD	105	108	573	97.0%	14.4%	va1	-205.8	1433	VA	MD
TN	127	130	0	97.5%	100.0%	md1	262.0	262	MD	PA
KY	124	127	0	97.4%	46.3%	**tn1**	2526.5	5455	TN	KY
IL	534	538	0	99.4%	65.4%	ky1	518.0	792	KY	IL
IN	293	296	0	98.9%	42.7%	ky2	412.6	966	KY	IN
OH	460	464	0	99.3%	100.0%	ky3	1178.0	1178	KY	OH
WV	65	69	0	95.3%	24.6%	ky4	294.4	1195	KY	WV
PA	388	391	0	99.2%	0.8%	il1	-16.4	2099	IL	IN
NY	614	617	0	99.5%	5.2%	in1	103.3	1975	IN	OH
NJ	347	350	0	99.1%	100.0%	oh1	830.0	830	OH	PA
MA	167	209	330	79.7%	100.0%	oh2	-9.0	9	OH	WV
CT	88	91	0	96.4%	12.1%	wv1	220.0	1811	WV	PA
RI	38	41	0	92.0%	54.1%	**pa1**	1338.7	2474	PA	NJ
NH	0	34	0	0.0%	100.0%	pa2	-415.0	415	PA	NY
ME	0	41	0	0.0%	53.3%	ny1	394.8	740	NY	CT
SUM	7,632	7,815	7,632			ny2	-432.1	576	NY	MA
						nj1	991.8	1380	NJ	NY
						ct1	306.6	439	CT	RI
						ri1	269.0	269	RI	MA
						nh1	0.0	330	NH	MA
						me1	0.0	500	ME	NH

Ideal Flow Efficiency=	**97.7%**
Actual Flow Efficiency=	**97.7%**

Figure 19. Optimal Flow for Concentrated Network

In the Dispersed Network, the network flow efficiency in the intact condition is nearly equivalent to the Concentrated Network's efficiency. However, flow in individual pipelines varies considerably. Again, though the solutions are not unique, some general trends can be identified. In the Concentrated Network, all of the pipeline capacity joining Texas and Louisiana (tx1) is used. As expected, flow from Texas to Louisiana is reduced significantly in the Dispersed Network, dropping from 1310 to 368.8 MMcf/d. Since there is relatively little pipeline capacity to carry gas from Maryland to markets in the Northeast, pipelines leading south and west from the mid-Atlantic, such as "va1" and "nc1," have considerably more flow in the Dispersed Network. For some pipelines, such as those linking North and South Carolina (sc1) and Georgia (ga1), the direction of flow is even reversed.

Nodes	Supplied	Demand	Import	% Demand Satisfied	% Pipe Capcity Used	Link Name	Flow	Assumed Flow Capacity	from	to
TX	1,946	2,202	2,315	88.4%	28.2%	tx1	368.8	1310	TX	LA
LA	720	720	1,719	100.0%	23.3%	**la1**	1367.5	5873	LA	MS
MS	159	159	0	100.0%	3.3%	ms1	-187.9	5631	MS	AL
AL	218	218	0	100.0%	32.8%	**ms2**	1396.7	4258	MS	TN
FL	413	413	0	100.0%	28.6%	al1	412.7	1442	AL	FL
GA	221	221	694	100.0%	30.9%	al2	-818.8	2648	AL	GA
SC	92	92	0	100.0%	26.3%	ga1	-346.0	1314	GA	SC
NC	126	126	0	100.0%	34.4%	sc1	-438.1	1275	SC	NC
VA	156	156	0	100.0%	51.9%	nc1	-564.5	1088	NC	VA
MD	108	108	1,091	100.0%	50.3%	va1	-720.5	1433	VA	MD
TN	130	130	0	100.0%	100.0%	md1	262.0	262	MD	PA
KY	127	127	0	100.0%	23.2%	**tn1**	1266.8	5455	TN	KY
IL	538	538	0	100.0%	65.8%	ky1	521.2	792	KY	IL
IN	296	296	0	100.0%	43.4%	ky2	419.1	966	KY	IN
OH	464	464	0	100.0%	100.0%	**ky3**	1178.0	1178	KY	OH
WV	69	69	0	100.0%	81.9%	ky4	-978.3	1195	KY	WV
PA	391	391	0	100.0%	0.8%	il1	-16.4	2099	IL	IN
NY	617	617	331	100.0%	5.4%	in1	106.5	1975	IN	OH
NJ	350	350	397	100.0%	100.0%	oh1	830.0	830	OH	PA
MA	209	209	607	100.0%	100.0%	oh2	-9.0	9	OH	WV
CT	91	91	0	100.0%	58.3%	**wv1**	-1056.0	1811	WV	PA
RI	41	41	0	100.0%	2.4%	pa1	59.5	2474	PA	NJ
NH	34	34	0	100.0%	100.0%	pa2	-415.0	415	PA	NY
ME	41	41	405	100.0%	2.6%	ny1	-19.1	740	NY	CT
SUM	7,559	7,815	7,559			ny2	-576.0	576	NY	MA
						nj1	106.3	1380	NJ	NY
						ct1	-110.5	439	CT	RI
						ri1	-151.3	269	RI	MA
						nh1	329.8	330	NH	MA
						me1	364.2	500	ME	NH

Ideal Flow Efficiency=	**96.7%**
Actual Flow Efficiency=	**96.7%**

Figure 20. Optimal Flow for Dispersed Network

The bar charts in Figures 22 and 23 show the natural gas demand and supply for each state, as well as the quantity imported, for the Concentrated and Dispersed Networks. As intended, the imported gas is more distributed in the Dispersed Network. However, it is interesting to note the demand in Texas is 170% greater than Louisiana, which has the second greatest demand, and dwarfs every other state.

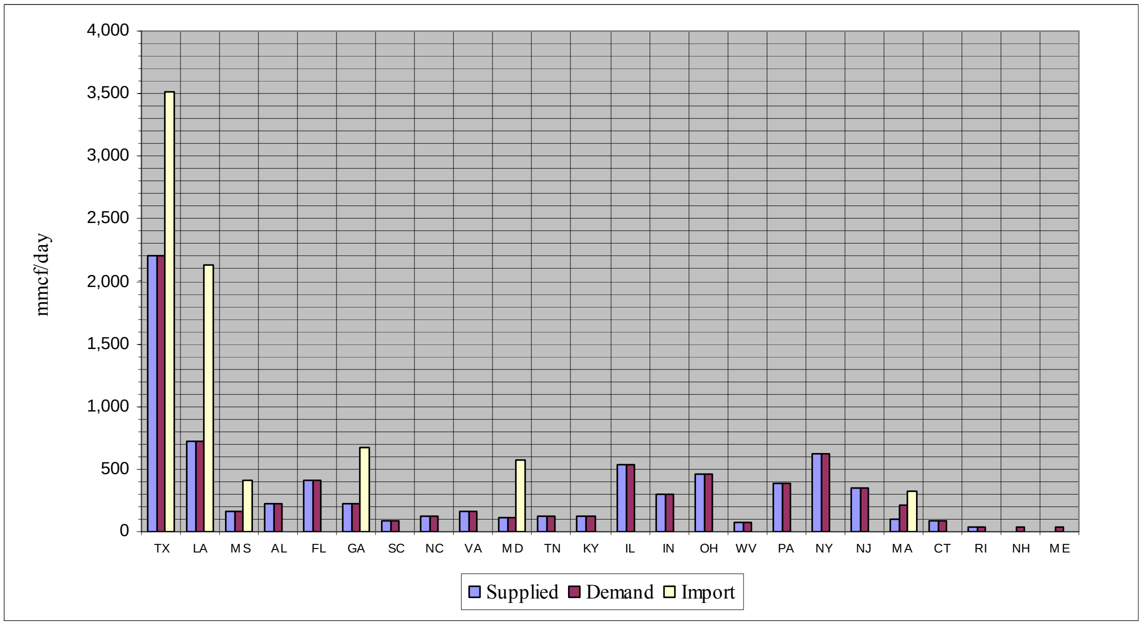

Figure 21. Natural Gas Supply, Demand and Imports for each node in the "Intact" Concentrated Network, demonstrating the centralization of imports in Texas (TX) and Louisiana (LA).

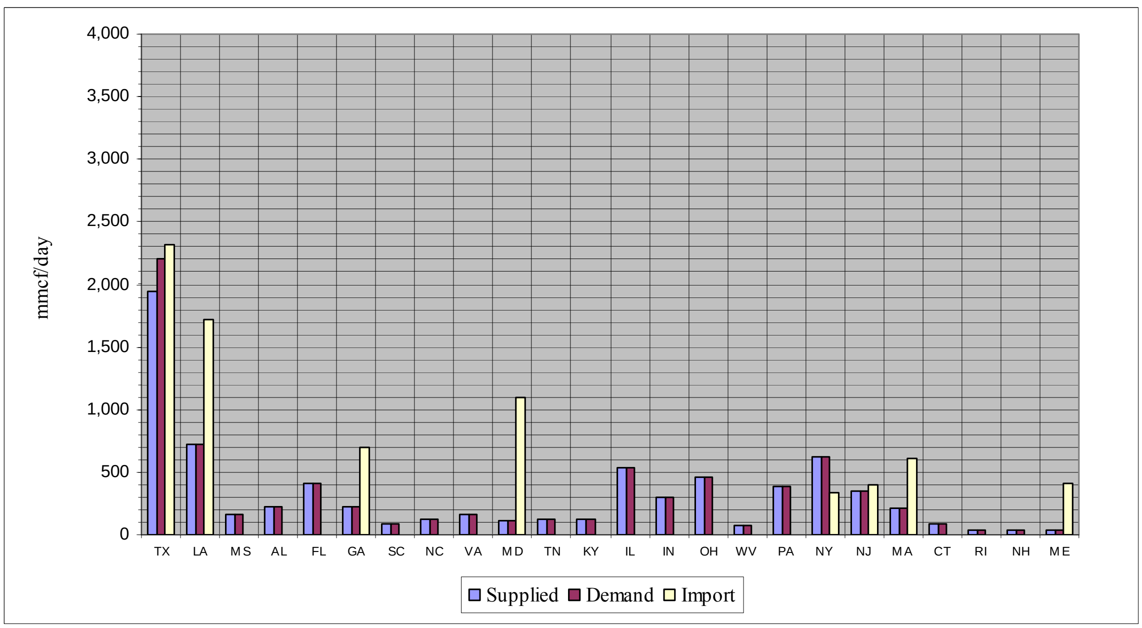

Figure 22. Natural Gas Supply, Demand and Imports for each node in the "Intact" Dispersed Network.

To determine the resiliency of each network, its ability to continue functioning after sustaining an attack or being impaired by natural causes, such as hurricanes, must be assessed. Damage to state nodes and interstate pipeline links is simulated by setting the flow in a given node or link to zero and reevaluating the network's flow efficiency. Each damage scenario was individually evaluated for each network. The results are presented in Figures 23 and 24.

Unlike the hub analyses, the results of the damage analyses are different for the Concentrated and Dispersed Networks. Damage to nodes and links located along the Gulf coast has a much greater impact on the Concentrated Network.

If links connecting Louisiana to Mississippi (la1), Mississippi to Tennessee (ms2), or Tennessee to Kentucky (tn1) are severed, flow in the Concentrated Network is reduced as much as 35%, which exceeds losses in the Dispersed Network by almost 150%. The differences in their ability to continue operating with damage to the link between Texas and Louisiana (tx1) is even more dramatic. The impact of damage to this artery in the Concentrated Network is more than ten times worse than it is in the Dispersed Network.

Of all the nodes and links, loss of the node representing Texas has the greatest impact on each network. In the Concentrated Network, network flow is reduced 46% if supply from Texas is suspended. Though still significant, only 30% of flow is lost in the Dispersed Network when subjected to the same damage.

The advantage of having redundant links in the network is illustrated by the absence of any impact on the flow in either network when the links connecting Illinois, Indiana, Ohio, Pennsylvania and West Virginia are damaged. As shown in Figure 23, there is no reduction in either network's flow when the individual links between these nodes (il1, in1, oh1, and oh2) are lost, because each is connected to more than one node and each of the links has ample flow capacity to accommodate the demand.

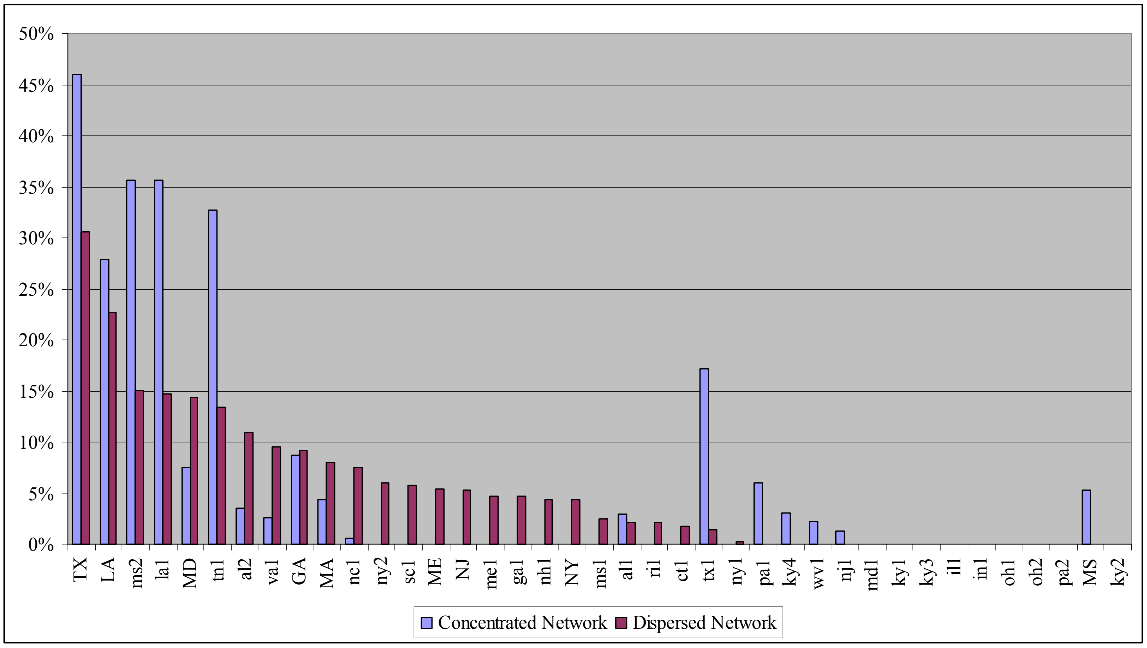

Figure 23. Percentage of network flow lost as a result of damage to individual network components.

Figure 24 compares the damage flow in the Dispersed Network to the damage flow in the Concentrated Network and illustrates the improvements in resiliency achieved by dispersing the LNG import terminals. For example, if both networks sustain damage to the link connecting Louisiana and Mississippi (la1), flow in the Dispersed Network is 32% greater than flow in the Concentrated Network. As expected, the Dispersed Network is much more resilient to damage along the Gulf coast.

Though the Concentrated Network is less impacted than the Dispersed Network for several damage scenarios, as illustrated by a “negative” improvement in figure 24, the difference between the flow in the networks is much less dramatic.

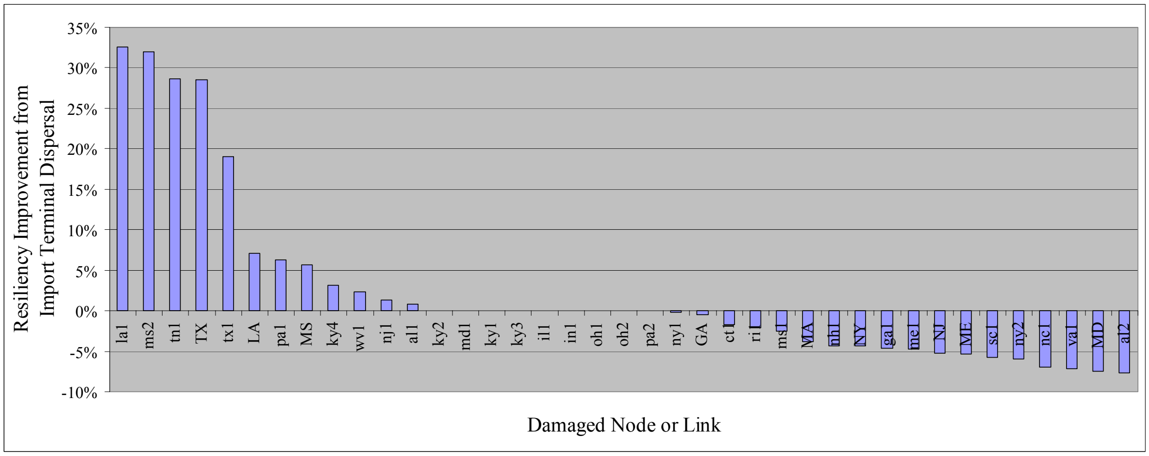

Figure 24. Comparison of damage flow in Dispersed and Concentrated Networks illustrates improved resiliency resulting from dispersal of LNG import terminals.

In addition, if all natural gas flow in the network were considered in lieu of only flow supplied by LNG imports the impact of damage on the Concentrated Network would be even more severe. The vast majority of all natural gas flows north from Texas and Louisiana, as discussed in Chapter II and illustrated in Figure 6, but only the flow from LNG import terminals located in the Gulf region is considered.

D. RESULTS SUMMARY

The Total, Concentrated and Dispersed Networks are all “scale-free.” They each have valuable hubs that could be deliberately targeted and exploited. In the Concentrated Network, Texas and Louisiana are the most connected nodes, each with a degree of seven. Links in the Dispersed Network are less concentrated. Louisiana, Kentucky, Pennsylvania, New York, and Massachusetts each have a degree of six.

The Concentrated and Dispersed Networks perform similarly in the intact, undamaged condition. The hub analyses determined the risk and vulnerability of each network. Because the elimination costs were assumed to be equal for all links and nodes in both networks, and the majority of the nodes and links in each have the same characteristics, the risk and vulnerability of the Concentrated Network are comparable to the risk and vulnerability of the Dispersed Network. Though the optimal budget allocation strategy necessary to minimize risk in each network is different, a given investment will produce similar results in both networks. The return on investment is non-linear and 80% of the network risk can be eliminated by strategically investing 20% of the assumed elimination costs.

Despite the similarities in the intact condition, the networks respond differently to damage. The Dispersed Network is more resilient. When individual supply nodes or links are lost, flow in the Dispersed Network is as much as 33% greater than flow in the Concentrated Network. In particular, the Dispersed Network is much less affected by natural disasters and deliberate attacks in the Gulf coast region, providing at least 25% more flow when subjected to the same damage. Although flow in the Dispersed Network is more impacted than it is in the Concentrated Network for eighteen damage scenarios, the difference in flow between the networks is less than 5% for more than half of these scenarios. At most, Dispersed Network flow is only 8% less than it is in the Concentrated Network and in this particular damage scenario, which includes damage to the link between Alabama and Georgia (al2), the Dispersed Network is still able to supply enough natural gas to satisfy 86% of the entire demand.

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VI. CONCLUSION

A. SUMMARY OF FINDINGS

1. Network theory can be used to model the nation's natural gas supply and distribution system and forecast how any given additional terminal will impact the risk, vulnerability, and resiliency of this critical infrastructure.

Existing LNG import terminals, natural gas storage locations, interstate pipelines, and each state's demands were modeled for the majority of the U.S. The physical location and capacity of several of the proposed LNG import terminals currently under review by state and federal officials were added to the model of the existing infrastructure. The relative risk, vulnerability, and resiliency of different possible network configurations were determined using the assessment capabilities in Network Analysis 4.0 and a flow optimization routine solved with Microsoft Office Excel 2003.

2. The impact of concentrating new LNG import terminals in one geographic region can be predicted.

Choosing from several proposed LNG import terminals currently under review by federal authorities or approved but not yet constructed, two possible network configurations were conceived, each with eight new LNG import terminals. One configuration geographically concentrated all of the new LNG import terminals in the Gulf states, while the other had only three new terminals in the Gulf and dispersed five of the terminals along the East coast. Each network was modeled and compared. The results of the hub and damage analyses demonstrate the natural gas supply and distribution network is more resilient and tolerant to damage if the LNG import terminals are dispersed. Concentrating the LNG import terminals along the Gulf coast exacerbated the impact of natural disasters and deliberate attacks in the Gulf region.

Selection of LNG import terminals for the networks assessed in this study was limited to those terminals currently proposed or already approved. However, given additional flexibility over the location and size of import terminals, the resiliency of the nation's natural gas supply and distribution network could be optimized further.

3. Network theory provides valuable insight that should be considered during the siting process for new LNG import terminals.

Many communities have significant concerns and local opposition can successfully derail attempts to site new LNG facilities. Network analysis will not allay the public's fear or persuade people to accept a LNG terminal in their "backyard." However, modeling the LNG import terminals, storage facilities, and pipelines as an integrated network and understanding its behavior will promote more informed decisions by industry, state, and federal officials.

B. RECOMMENDATIONS

1. The FERC and USCG should develop a complete network model of the nation's natural gas supply and distribution network.

Using reliable modeling and more sophisticated flow simulation tools, a detailed model of the entire natural gas supply and distribution infrastructure should be developed. The model and analysis methodology should determine the resiliency of the existing network and facilitate reassessment of the network with proposed LNG import terminals.

Like other critical infrastructures, the natural gas supply and distribution network is so extensive that it is not reasonable to protect all of it. A firm understanding of how this critical infrastructure behaves as a network and responds to potential changes will promote sound decisions by government officials.

Development of individual network models by the FERC and the USCG is discouraged. Interagency cooperation is necessary to avoid unnecessary duplication of effort. In addition, shared expertise will facilitate development and maintenance of an optimum network model. The existing Interagency Agreement between the agencies supports this partnership.[92]

[92] Federal Energy Regulatory Commission, "Interagency Agreement Among the FERC, USCG and RSPA for the Safety and Security Review of Waterfront Import/Export LNG Facilities," <http://www.ferc.gov/industries/lng/safety/reports/2004-interagency.asp> (Accessed 16 October 2006).

2. The criteria applied by federal officials during the siting review and licensing process should consider the impact a proposed facility will have on the nation's natural gas supply and distribution network.

The selection of new terminal locations is an important strategic decision that should be in alignment with national goals and initiatives. The addition of critical infrastructure must promote development of a network that is inherently robust, reliable, and resilient. The location of LNG import terminals impacts the health and security of the entire natural gas supply and distribution network and the ability of this critical infrastructure to meet the nation's increasing demand for natural gas. The disadvantages of geographically concentrating this critical infrastructure must be understood. Network theory can be used to compare alternative locations and inform decisions long before approvals are granted and significant resources are invested.

In the absence of a national strategic approach, the natural gas supply and distribution network will likely evolve in a manner that diminishes its resiliency and increases both the vulnerability and the consequences of natural failures and potential attacks. The federal government must use its authority to regulate interstate trade of natural gas to ensure proposals for development of additional infrastructure do not diminish the resiliency of the nation's natural gas supply and distribution network. Local, regional and national risks and benefits should be considered during the siting process. As part of this evaluation, the FERC and USCG must assess the impact of each proposed shore-side LNG import terminal and LNG deepwater facility on the existing network. Approval should only be granted for those import terminals that will improve the resiliency of the nation's natural gas supply and distribution system.

3. The FERC and USCG should take a more active role in the siting process and provide incentives to encourage new LNG import terminals in locations that significantly improve the resiliency of the nation's natural gas supply and distribution network.

The current siting process used by federal agencies to evaluate proposed locations is in dire need of improvement. It fails to effectively bring all parties together and determine the optimal solution for the present and future needs of the local community, state, greater region, and nation.

Local communities faced with the possibility of having LNG import terminals built in their backyards have difficult decisions to make. They are often confused by conflicting facts and opinions produced by the "experts." The public's fear creates tension and fuels emotional debates over the risk associated with LNG import terminals, which only serves to further polarize opposing parties. The stiff opposition in many communities may force the natural gas industry to continually concentrate new infrastructure along the Gulf coast in spite of the projections for demand, existing supply options, and pipeline capacity limitations and "backfill" opportunities.

This problem is not likely to be resolved on its own without some type of intervention. Unless changes are made, the result will likely be the steady emergence of increased vulnerabilities that require costly protection measures and degrade the resiliency of the network, with grave implications for U.S. economic prosperity and national security.

In lieu of seeking tighter regulatory controls and using strong arm tactics to overrule local concerns, the federal government must take a more active role in the siting process in those locations where the presence of a LNG import terminal would improve the resiliency of the nation's natural gas supply and distribution network. The FERC or USCG should help industry establish effective communications with all stakeholders, understand public concerns, earn social trust, achieve acceptance by the local community, and obtain the political support necessary to successfully site LNG import terminals in locations that improve network resiliency.

Economic incentives, tax benefits, grants, and other resources and investments should be used, where appropriate and necessary, to address and overcome local concerns. Since it is too costly to protect the entire natural gas supply and distribution network, it may be more cost effective to dedicate resources to build a more resilient network rather than continue to develop and protect one that is more vulnerable. Nearly

$2 billion in grants have been provided by the DHS to strengthen security of critical infrastructure.[93] Some of this funding should be dedicated to improving network resiliency.

4. The federal government should immediately consider these recommendations.

The explosive growth in LNG imports has spawned a huge wave of natural gas infrastructure development. The present opportunity to shape and intelligently structure the nation's natural gas supply and distribution system is unprecedented. After industry has built the capacity needed, additional investments of this magnitude are unlikely. Such an opportunity rarely presents itself and must not be squandered.

To provide optimum benefit, these recommendations must be adopted immediately and used to evaluate the LNG import terminals currently proposed and under review.

5. The Department of Homeland Security should consider using network theory to evaluate other critical infrastructures.

The principles and theory applied to the natural gas supply and distribution network in this study could also be applied to other infrastructures that are interconnected and operate as a network, such as the electrical power supply and distribution system. The insight provided by the application of network theory could help DHS develop priorities and determine funding initiatives related to the protection of critical infrastructure.

[93] U.S. Department of Homeland Security, "DHS Announces $445 Million to Secure Critical Infrastructure," press release, 9 January 2007, <http://www.dhs.gov/xnews/releases/pr_1168366069190.shtm > (9 January 2007).

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